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ORIGINAL ARTICLES.

The Centenary of the British Association for the Advancement of Science.

OF late years, owing to the great volume of original papers sent in to the GEOLOGICAL MAGAZINE, it has not been possible or desirable to devote space to the proceedings of the British Association, as was the custom under the editorship of the late Dr. Henry Woodward; but it is manifestly impossible to pass over in silence the celebration of its Centenary, which has just been held in London, under the presidency of the Right Honourable General J. C. Smuts. The personality of the President alone would be sufficient to mark this off as a special occasion, but from the point of view of the geologist there is much more in it than this.

The parent of the British Association was the Yorkshire Philosophical Society. The idea was apparently first set forth in a letter from Sir David Brewster to John Phillips, then secretary of the said society, the nephew of William Smith and afterwards Professor of Geology at Oxford. This suggestion was eagerly taken up by Phillips and by the Rev. William Vernon Harcourt, himself a competent geologist, as is shown by his description of the Pleistocene deposits of Bielbecks in East Yorkshire. The first meeting was held in the Museum of the Yorkshire Philosophical Society at York, under the presidency of Lord Milton, a county magnate, but it is noticeable that at the second meeting at Oxford the President was the Reverend William Buckland, Professor of Geology in that University, while the third meeting was at Cambridge, when the President was the Reverend Adam Sedgwick, also Professor of Geology in that University. Hence we may fairly say that geology played a dominant part in the early history of the Association.

The *Report* of the first meeting affords some interesting reading to modern scientific workers. The list of officers and committees shows some remarkable contrasts with recent similar occasions in the scarcity of knights and the enormous number of clergymen.

Evidently there was then no conflict between religion and science, which is a purely Victorian development, and there is no parallel to the constellations of titles of honour in recent scientific gatherings.

The list of those forming the Sub-Committee for Geology and Geography is indeed remarkable ; it includes Buckland, Conybeare, Grey Egerton, J. D. Forbes, Murchison, Phillips, Greenough, Sedgwick, and William Smith. Although the *Principles of Geology* had just been published it does not appear from the records that Lyell took any part in the York meeting, but his name appears in the list of members at the second meeting at Oxford. It is to be regretted that the first *Report* contains no general list of members, who numbered altogether about 350.

However, from our present point of view, the features of greatest interest are contained in the *Report* of the Oxford meeting. Here we find voluminous reports on the then position of natural science, commissioned at York and presented at Oxford. That on geology, by Edward Conybeare, is indeed a masterly presentation of its subject, with in parts a strangely modern ring ; it could be read with profit by many of the most up-to-date geologists of the twentieth century. It is of course heavily handicapped by the vagueness of current knowledge of anything below the Carboniferous and it is interesting to find an innocent remark to the effect that Professor Sedgwick had started to investigate the rocks of North Wales, while Mr. Murchison had also begun on Shropshire. In reading this report it must of course be remembered that at that time petrology did not really exist, and that ideas on igneous rocks were of the most vague description. Granite and basalt were more or less comprehended, while " trap " covered a multitude of ignorance. The early recognition of granite and basalt in fact meant a great deal more than the men of that time were able to grasp.

The chief lesson to be learnt from a study of geology, as presented at the first and second meetings of the British Association, is shortly this : that the science had freed itself from the absurdities of Wernerism, eighteenth century cosmogonies, and " Theories of the Earth " based on speculation rather than on facts, and had definitely embarked on the course which has led to its present position as one of the sciences of observation and inference, which have substantially advanced the material progress of mankind. Whether the dominance of the coal, oil, salt, and mining interests in the economics of the world is of ultimate moral and spiritual benefit is of course another and quite different question, which cannot now be answered. Nevertheless it is interesting and significant to find that in 1831 geology had definitely become a modern science, while biology, so conspicuous in the controversies of thirty years later in the same arena, then played a very subordinate part. The *Beagle* sailed from Devonport on the 27th of December, 1831. This date may perhaps be regarded as the birthday of Darwinism,

and therefore to a very large extent of modern evolutionary geology. The theory of natural selection may be, and probably is, inadequate to explain the facts, but at any rate it gave the impetus and drew attention to the lines along which evolution is eventually to be worked out.

On the Mechanics of Mountains.

By Harold Jeffreys, F.R.S.

BY a curious coincidence, a length of the order of 40 kilometres turns up in geophysical discussions of several different crustal phenomena.

The typical crustal structure in the continents, as revealed by the study of near earthquakes, consists of an upper igneous layer that transmits compressional waves with a velocity of 5·5 km./sec., an intermediate one where this velocity is about 6·3 km./sec., and a lower one where it is about 7·7 km./sec. The depth of the upper layer is about 10 km., that of the intermediate one about 20 km., while the lower one appears to extend downwards for at least 400 km. and possibly half-way to the centre of the earth. From petrological considerations and laboratory tests on the elastic properties of rocks under pressure it seems practically certain that the upper layer is granite and the lower one a rock consisting mainly of olivine, such as dunite. The identification of the intermediate layer is more open to doubt. The velocity is definitely too low for crystalline basalt, which one might otherwise consider the most probable material; it fits vitreous basalt or tachylyte, though Holmes has suggested other alternatives. Eclogite has been suggested for the lower layer, but seems improbable. L. H. Adams and R. E. Gibson [1] have found that the velocity in eclogite is likely to be about right, but the real objection to it, it seems to me, is precisely what to some seems a recommendation, that it is a mixed crystalline rock. In a slowly solidifying earth gravity would separate crystals according to density as fast as they were formed, and we should not get a layer of mixed rock extending half-way to the centre of the earth, but a succession of different layers of fairly pure minerals.

The precise identification of the layers is, however, not essential to the present paper. What is relevant is that the density of granite is about 2·65, those of all the admissible rocks for the intermediate layer about 2·85, and those of both dunite and eclogite about 3·3.

The thickness of the sedimentary layer above the granite is variable; its average value seems to be about 2 km.[2] In all, the

[1] *Proc. Nat. Acad. Sci.*, xv, 1929, 713–24.
[2] *Gerlands Beiträge zur Geophysik*, xxvi, 1930, 58–60.

thickness of the sedimentary, granitic, and intermediate layers together is, on an average, about 32 km.

These estimates are checked by several other lines of investigation, which will be found in the second edition of my book *The Earth*.

The general principle that regions of elevation, such as mountain systems, are associated with lighter matter below sea-level, is now well established, and it seems that in such regions there must be an extra thickness of the light upper layers. This is in accordance with most geological opinion, though a different interpretation is given by some geodesists, notably Dr. W. Bowie. If we consider the compensation to be due to a defect of mass concentrated at a certain depth, Heiskanen has shown that the best representation of the values of gravity in mountainous regions is given by taking this depth to be about 50 km. In reality the "root" must be within the region normally occupied by the matter of the lower layer, but by lighter matter in the case of mountains, and therefore its mean depth cannot be much over 30 km. The excess of the computed value over this is to be attributed to the fact that the compensation is not absolutely local, but is spread out horizontally for some distance around the surface inequalities; compensation at any depth can be shown to produce precisely the same effect on gravity as regional compensation, spread through a suitable distance, at any smaller depth. But if the depth of the weak region where the isostatic outflow takes place was much over 30 km., the bending of the upper crust by a surface load would distribute the depression so widely that the equivalent depth of local compensation would be greater than 50 km. It appears that the depth of the asthenosphere is between 30 and 50 km., and probably nearer the former value.

The crustal shortening to be expected when the earth's crust gives way under the stresses due to progressive contraction of the interior is about 40 km. The elastic constants and crushing strength of granite are such that it yields when compressed by about 1 part in 1,000 of its length. If the interior underwent a radial contraction by 1 part in 1,000, the outer crust would be under a greater stress than it can stand, and would accommodate itself to the new dimensions by some kind of folding or fracture. The circumference of the earth being 40,000 km., the required shortening would be 40 km.

The crustal shortening involved in the formation of a great mountain system is also of order 40 km. As this statement will be strongly queried by many geologists, I give the evidence for it more fully than for the others. Consider the effects of increasing locally the thickness of any of the three outer layers by 10 km. 10 km. of sediments of density 2·4 will displace 7·3 km. of dunite of density 3·3 and leave an elevation of the surface of 2·7 km. An extra 10 km. of granite will displace 8·0 km. of dunite and leave an elevation of 2·0 km. An extra 10 km. of the material of the

intermediate layer will displace 8·6 km. of dunite and leave an elevation of 1·4 km. Suppose then, that some crustal movement shortens the crust along a certain strip by half its width. The normal thickness of all the upper layers is doubled. The extra 2 km. of sediments leave a surface elevation of 0·5 km. ; the extra 10 km. of granite give an elevation of 2·0 km. ; the extra 20 km. of the intermediate layer give one of 2·8 km. The total elevation is 5·3 km., more than the height of Mont Blanc or Pike's Peak. If the Rocky Mountains or the Alps had been formed by a crustal shortening as great as 2 : 1, the mean height of the land within them would be greater than their maximum height is now.

It must be recalled that these are the ranges where isostasy is best verified, and that the above determination of crustal structure from seismology was made from earthquakes in Western and Central Europe, and has been found by P. Byerly to fit California.[1]

To obtain an estimate of crustal shortening from these principles, we must allow for the changes in the topography of mountainous regions since they were formed. The original uplift probably produced a plateau ; the present peaks are due to the carving out of valleys by denudation. This lightening of the crust must have produced an isostatic inflow and therefore a general raising of the land, and in particular of the mountain tops. It seems probable that the present height of the highest mountains is somewhat greater than their original height, on account of this lifting effect. I estimate that the primitive height of the Alps and Rockies was about 3·2 km., and of the Himalayas 5·8 km. This implies crustal shortenings for the first two in the ratio 1·60 : 1, and for the last as 2·1 : 1. Taking the present width of the Alps and Rockies as 100 km., and of the Himalayas as 160 km., we infer crustal shortenings of 60 km. for the first two, and 180 km. for the last.

The total crustal shortening implied by the thermal contraction theory is not known accurately, but appears to be of order 200 km. If there have been six major periods of mountain formation, this offers an average of 33 km. for each. It may be said that the thermal contraction theory is not generally accepted ; but there are certainly no grounds for accepting any other, and it seems a perfectly legitimate procedure to consider its consequences as a check on the other estimate.

Now it is familiar that far greater horizontal movements than 60 km. have been claimed as necessary for an explanation of the structure of the Alps and Rockies ; current estimates run into hundreds and some even into thousands of kilometres. The question is whether the discrepancy is real or apparent. With regard to the argument just given, I need only say that where other geophysicists disagree with my interpretations, their views

[1] *Bull. Seism. Soc. Amer.*, xvii, 1928, 203–6.

of crustal structure would increase the discrepancy. Nor am I prepared to dissent from the geological conclusions, the main features of which seem to me to be well substantiated. My belief is that the only possible conclusion from the comparison of the results is that the crustal shortening and the horizontal movement measurable at the surface are two very different things.

Let us consider first the conditions just before uplift begins. My attention was attracted to this problem by the recent paper of Drs. Elles and Tilley on Highland metamorphism, following a visit to the Ballachulish country conducted by Professor E. B. Bailey. The zone of uplift is usually (I think always) one where there has previously been unusually heavy deposition of sediments. Such a phenomenon, as I have shown in a recent paper,[1] will be associated with a great disturbance of the normal thermal state. Mere compression would produce little change of temperature, but the new heat generated by radioactivity in the crust has less free access to the outer surface than before, and if there were no other disturbing factor it would lead to a permanent increase of the temperature in all the upper layers. It appears that if 10 km. of sediments lie for 130 million years, the temperature at their base will rise to about 250° C., which will be enough to permit the observed amount of metamorphism.[2] At the same time the temperatures below them will be increased; it appears that a rise in temperature of 100° or more is to be expected through a range of depth of order 100 km. Consequently, all layers will be weakened; and therefore when compressive stresses become too great to be resisted by the crust it is the regions of heavy sedimentation that will be the first to give way. The general association of mountain formation with previous sedimentation therefore seems to be explained.

Now consider the nature of the yield when it takes place. The movements produced must be such that they do lead to the requisite reduction of surface. A vertical fracture or a horizontal splitting will not do. There must be either an oblique fracture with sliding along the thrust plane, or a general thickening. Relief by thrusting would mean that the whole of the crust down to the asthenosphere, say, a thickness of 40 km., would be overthrust for a distance of about 60 km. This means that the thrust plane would have to be inclined to the horizontal at about 35°. Since it is usual for fracture to take place at an inclination of about 45° to the principal stress,

[1] *Monthly Notices of the Royal Astronomical Society*, Geophys. Suppl., ii, 1930, 323–9.

[2] Dr. Tilley says (*Mineral. Mag.*, xxi, 1926, 50): "The absence of almandine in the normal contact-aureole, (and) the visible evidence of its replacement when introduced into the sphere of influence of igneous intrusions, conspire to demonstrate that the iron garnet is unstable under the conditions prevailing in normal contact metamorphism." The temperature of formation of this mineral must naturally be considerably lower than that of its decomposition.

there is nothing inherently impossible in this, and it is probable that the yield would begin in this way. But there are several reasons why it could not continue until a thrust of such dimensions was completed. The precise nature of the yield depends on the physical state of the material; putty and brick do not behave in the same way when overstrained. Cold rocks at atmospheric pressure usually give way by oblique fracture, but at high pressures or high temperatures laboratory experiments show that the yield takes place by more or less continuous adjustment. Geology produces abundant instances of both types of yield, and it is, I think, generally considered that faulting and thrusting imply low pressures and temperatures and therefore small depths, while schistosity and continuous folding imply high pressures and

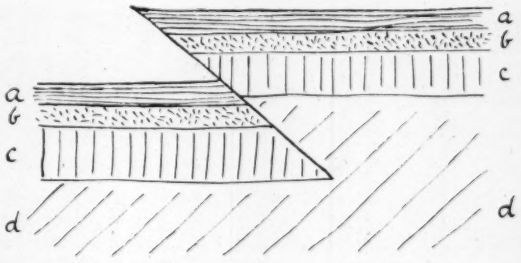


FIG. 1.—Result of crustal shortening by oblique fracture. *aa*, sediments *bb*, granitic layer; *cc*, intermediate layer; *dd*, lower layer.

temperatures, and therefore that the rocks involved were deeply buried. Since this occurs in rocks that have been buried only 10 km. or so, we must expect it also in the still deeper rocks of the granitic and intermediate layers. The lower layer may, therefore, escape being thrust over the intermediate one, and the intermediate over the granitic one, by yielding within themselves so as to give a local thickening instead.

It is obvious that the resulting process must be extremely complicated. We have cold, superficial rocks yielding by fracture, overlying heated sedimentary rocks yielding by continuous adjustment, and themselves overlying three igneous layers all with different mechanical properties. It can end only when the stress-differences at all points have been reduced below the local strength of the materials. It must be mentioned also that although in superficial conditions continuous adjustment and low strength go together, this is certainly not true at high pressures. The work of F. D. Adams and Bridgman has shown that while the stress-difference needed to produce yield in solids increases with the mean pressure, the yield, when it does take place, is more likely

to be by continuous adjustment. But in any case it is wildly unlikely that the properties of the various layers will be in just such an adjustment that the yield will proceed so as to give directly a uniform thickening of the upper layers, combined with just such an outflow in the lower layer as will give isostasy. It is more likely that the failure in the upper layers will result in their being crushed together by sliding over the lower layer, before the lower layer has had time to adjust itself to the local load by outflow. Then there may be a local thickening of the upper layers by 20 km. or so on a belt about 60 km. wide, leaving a plateau 20 km. in height, a remarkable picture.

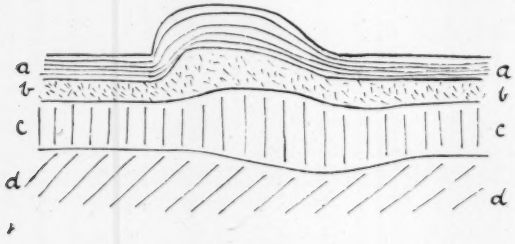


FIG. 2.—Result of crustal shortening by continuous yield.

In fact such a condition of things could not persist. The crushing strength of granite is about $0{\cdot}8 \times 10^9$ dynes/cm^2.,[1] and corresponds to the pressure under about 3 km. of granite. A cliff of this height would fracture under its own weight. The complete adjustment of the outside to relieve the compressive stresses due to contraction would introduce a new, but local, set of stresses seven times as great.

The solution seems clear when the problem is stated. The compressive stresses are there, and they can be relieved by crustal shortening and in no other way. But crustal shortening is not the end of the matter, for it implies a new set of stresses due to gravity, which has so far not been considered at all. These are greater than the strength of the material can sustain, and therefore a further and new type of yield must take place. Whenever an elevation over 3 km. has been produced, either fracture or flow must set in ; whichever it is, its general effect will be the spreading out of the elevated rocks over the surrounding country. Thus the flat overflows known as nappes are a natural consequence of the theory ; but they are directly attributable to distortion under gravity, crustal shortening being the primary but not the immediate cause. Further, the phenomenon of one nappe being " thrust " over the top of another, so notable a feature of Alpine and Highland geology, follows immediately, for we need only consider

[1] 10^9 dynes is about a ton weight.

the gravitational movement to recommence when the primary elevation has proceeded for a second 3 km.

It may be remarked that though putty, when stretched, may undergo a large continuous yield, it does ultimately break. Similarly in nappe formation by flow it is possible that the extreme end may break off and slide down the gentle slope by itself, giving a klippe. I do not wish to emphasize this mechanism, but it does

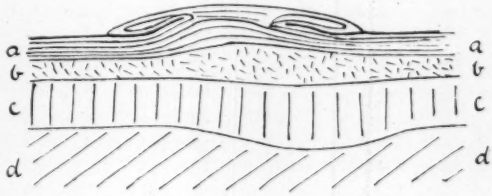


FIG. 3.—Secondary result of crustal shortening, with outflow above due to gravity.

not appear obviously absurd, and if it is correct it would imply that in some cases there may never have been a continuous connection between the present position of a klippe and the main nappe.

It is also evident that as the movement of elevation proceeds, the uplifted rocks must be lifted above those that have already adjusted themselves, which themselves will in general slope downwards from the region of yield. It is therefore to be expected that later nappes will overspread the earlier ones and finally come

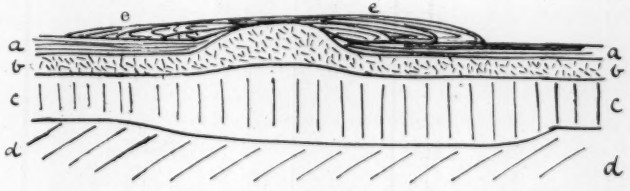


FIG. 4.—Ultimate result of outflow. *ee*, nappes.

to rest on the undisturbed regions beyond them, possibly producing drag-folding in the latter by friction. This again agrees with the facts. Again, the phenomenon of "back-folding", which is difficult to understand when nappes are considered to be due to horizontal thrusting, is entirely natural when we consider an elevated region of weak rocks spreading out under gravity. Flow may well take place in both directions from the main elevation. Whether it will do so in any given case will probably depend on the special circumstances.

The flow of the rocks would presumably be slow, for, though weak, they would have a high viscosity and would be moving in comparatively thin sheets. Isostatic adjustment may well keep pace with the spreading. The outflow from the central region would lead to a thinning of the excessive quantity of sediments there, and might ultimately expose the granitic layer. Something like 16 km. of sediments would have to move away to form the nappes, not an unreasonable amount, and a central massif of granite, showing signs of considerable metamorphism, would remain. The existence of the gneissic core of Mont Blanc is again in agreement with the theory.

It might appear that if the sedimentary layer just before elevation exceeded its normal thickness by 8 km., a smaller amount of crustal shortening would be needed to give a range of a given height; and if the sediments were simply added to the outer surface and compensated by outflow in the lower layer this would be so. But it seems probable that the weakening of the intermediate layer below the region of sedimentation leads to outflow in that layer as well, and that effectively the sediments are compensated in the course of their deposition at the expense of the intermediate layer. In that event the amount of shortening needed would have its normal value. There is confirmation of this view in the fact that it makes it possible to see how 10 km. of sediments can be deposited in water with an initial depth of only about 1 km. In a sense the sediments make their own geosyncline, or at any rate complete it when it has once started.

The Himalayas are obviously abnormal, especially when we consider them in conjunction with the other great ranges to the north. It is very hard to see how so great a crustal shortening as they suggest can have been restricted to a range extending over only about 30° of longitude. There seem to be two possible solutions. The crustal shortening in Central Asia may have arisen from some special local cause; or it may actually have had its normal value, but have produced an unusually great elevation on account of the presence of an unusual thickness of light rocks. In the latter case we must regard the region as having been originally an ocean, which later became completely filled with sediments. I think that additional data are needed before we can decide between these alternatives.

Summary.

It appears that the geophysical approach to the problems of crustal dynamics leads to a theory of mountain formation that covers the main features of the formation of nappes and is in general agreement with other geological evidence. The chief novelty is in the recognition of the importance of the spreading under their own weight of the rocks uplifted as a result of crustal shortening.

Note on the Spongy Ironstone of Angola.

Extract from a Report by Dr. Malcolm Burr and P. S. Nazaroff to Sir Robert Williams, Ltd., by whose kind permission it is published. Translated from the Russian by Dr. Burr.

By P. S. Nazaroff.

(PLATE XIV.)

In the interior of Africa, in the high region of the Portuguese colony of Angola, in localities lying at an altitude of from 3,000–4,000 feet, where the soil consists of a thick layer of sand, clearly derived from the disintegration of the underlying sandstones, one constantly meets with peculiar and interesting outcrops of iron ore in the form of brown ironstone (limonite) of a spongy texture. This brown ironstone has in some places a greyish metallic colour, in places a reddish-brown, brown, brownish-yellow, or other tint characteristic of this hydrated iron oxide, but in structure it is different from all other varieties of this kind of iron ore. The entire mass is full of irregular cavities exactly like those in an ordinary toilet sponge or in pumices, and gives the impression of a ferruginous mass inflated with gases. It also recalls the unforged iron produced in the old-fashioned methods of " burning out " metallic iron direct from the ore used by ancient metallurgists.

It occurs in separate lumps and bosses of various sizes directly in the sand. These measure from 20–30 cubic inches up to very substantial masses, running to several hundred cubic feet in capacity. (See Pl. XIV.) Sometimes these masses are almost completely buried in the sand, only their upper surface being exposed, and sometimes they appear like great boulders or elevations in the form of small crags, especially if they happen to lie at the edge of a steep slope or small valley ; sometimes they form an outcrop like a prominent ridge of rock or cover a considerable surface of the ground.

As I have said, this ironstone is deposited for the most part on sand, but sometimes it occurs on laterite. It is not a part of any definite bed, nor have the lumps deep roots, but lie near the surface to which they sometimes give a brown, brick-red, or yellowish-brown colour.

If these ferruginous masses are dug out, it is clear that atmospheric waters, penetrating the spongy cavities, stain the surrounding sand. Their presence near the sources of streams and brooks gives them a strong ferruginous rust colour.

The question arises, what can be the origin of these curious masses of ironstone lying scattered about the country, in the great majority of cases among alluvial sands or more rarely on the laterite ?

The first author to call attention to them was Livingstone, who

wrote in 1857, " the rocks of Gonye area are reddish grey sandstone nearly horizontal and perforated by madrepores, the holes showing the course of the insect in different directions. The rock itself has been impregnated with iron and that hardened forms a glaze on the surface . . . an appearance common to many of the rocks of this country." (*Missionary Travels and Researches in South Africa*, 1857, p. 498.) Gonye appears to be on the Upper Zambezi, no great distance from the district to which I am referring.

Other observers have attributed them to volcanic origin. The most natural explanation of course is that they have been formed in bogs, as their form and structure in some cases recalls that of bog ore, but their occurrence on high and dry localities, their total absence from boggy places, their boulder-like character, and strange spongy structure are powerful arguments against such a theory.

We find an analogous structure, however, in the material composing the innumerable termite nests which are so characteristic a feature of Angolan scenery. When we compare these two objects, which at first glance appear so totally different, the identity of the internal structure at once becomes obvious, as well as of the external appearance, the only difference being in the material forming the walls of the cavities. But there is clearly a substantial iron content in the walls of the termitaria, so that this difference is really not so great, being only quantitative.

Here we must add a few words on the material of which these termite nests are composed. People who have not seen them in their natural surroundings imagine something resembling an ant's nest, to which, as a matter of fact, they have no resemblance. Termites' nests when on the ground, for they also occur on trees, consist of a very compact, hard material resembling cement and totally different from the ground on which they are built. This material has very valuable properties which give the termitaria great significance for white residents in this part of Africa. We may go so far as to say that if there were no termite nests in this district, the white population would have no building material for their houses other than wood and grass, as there is nothing else but sand and hardly suitable timber. But this termite earth makes an excellent binding material which, when mixed with sand, yields a very good, strong brick, as hard as stone, as well as an excellent plaster which acts as a light, but solid, substance for filling the skeletons of buildings ; the walls are made of a frame of thin laths lashed together with strips of bark with the interstices filled in with the spongy matter of the termite nests. With this same substance they pave their roads, streets, and yards, getting a firm, smooth surface something like asphalt, which throws off the rains and floods very well, and last but not least, when mixed with sand, burns into an admirable brick with which the more important buildings in the towns are constructed.

All these valuable properties of the termite earth are due to the

PSEUDOMORPH OF TERMITARIUM IN HAEMATITE ON THE RIVER CAMASAMBA, DISTRICT OF MOXICO, ANGOLA.

To face p. 443.]

complex physical and chemical processes which a mixture of mineral and organic matter undergoes owing to the action of the termites. The substance of the termitaria is totally different from that of the soil on which they are built, in this case consisting of an incoherent quartz sand, and they contain a great deal of iron. Sometimes the walls of the internal cavities have a metallic appearance due to the presence of iron oxides and in such cases a nest, in outward appearance, is indistinguishable from the ironstone mentioned above. Sometimes one comes across a gradual transition from the fresh termitarium to the ferruginized form. The large quantity of iron deposited in the walls does not appear to agree with the termites and they abandon the nest which is then sometimes occupied by ants. The actual process of ferruginization of the nest is independent of the activities of the termites themselves and is clearly a process of deposition of iron from solution by the action of organic substances. Atmospheric waters, soaking into the soil during the wet season, dissolves out the iron salts from the soil, in our case from the sand. These are then absorbed by the termite nests and deposited in its walls as iron oxide. For this conversion it appears necessary for the entire mass of the termite nest to be buried in the soil.

But this process of ferruginization is not the only one to which the termitaria are exposed in nature. There is an analogous phenomenon of silicification of the nests, producing a pseudomorph in silica. Near rocks rich in silica, such as the quartzose sandstones or quartzites, old termitaria are converted into a completely silicified but spongy rock, sometimes with parts of the pores filled with sand.

The ferruginization of the termite nests, as may be easily observed, begins at the surface and proceeds gradually inwards. This process occurs too in soils which appear to consist of clean, white sand, seemingly quite free from iron, but it is most complete on lateritic soils which have a high iron content.

Laterite, as is well known, contains a high percentage of hydrated oxides of iron arising from the decomposition of ferro-magnesian silicates in crystalline felspathic rocks. In places, under the action of the abundant moisture and actinic rays of the sun, the iron oxides are separated out in the form of small globular concretions of pisolitic structure, forming pea-ore, which is uncommonly like bog-iron ore. Sometimes this ore covers an extensive area and forms substantial masses. Often enough ferruginized termite nests occur on it, distinguishable from the concretions by their spongy texture and the fact that they occur in isolated boulder-like masses, whereas the pea-ore forms flat surfaces of considerable extent.

On a lateritic soil both these processes of the separation of iron oxides take place side by side, both owing to the tropical climate, damp heat, and actinic rays of the sun. The latter, in

the absence of moisture in dry deserts, are capable of reducing iron on the surface of rocks containing ferruginous minerals and forming the so-called " desert-sunburn ".

How much time is required for the ferruginization of a termitarium and to what epoch are to be referred the formation of the ferruginous termite-boulders and rocks ? As the elevated regions of Central Angola have existed as a continental area at least since the Trias and the termites themselves are an exceedingly ancient group, there has evidently been time enough for this process, but we can still observe it taking place in various degrees of completion.

These observations lead us somewhat to modify our opinion of termites as exclusively harmful insects. Apart from the production of iron these minute creatures play a not inconsiderable part in supplying man with building material of a very valuable character.

On Corundum-Spinel Xenoliths in the Gabbro of Haddo House, Aberdeenshire.

By H. H. Read, University of Liverpool.

1. Occurrence.

In the neighbourhood of Haddo House, between Methlick and Ellon, some 20 miles north of Aberdeen, there is a considerable body of gabbro that has been named the Haddo Mass.[1] This intrusion is later than the general metamorphism of the Dalradian country-rocks and, from its resemblance to certain dated intrusions, earlier than the local Middle Old Red Sandstone. It belongs, therefore, to the Younger Gabbro portion of the Post-Movement Phase in the igneous history of North-East Scotland.[2]

The rocks of the Haddo Mass were called diorite by J. S. G. Wilson [3] in the Geological Survey Memoir of 1886, but examination by the writer during recent years shows that the mass consists of two main rock-types—olivine-gabbro and norite. The olivine-gabbro is free from xenoliths of country-rock, whereas the norite is always crowded with such material. Among these xenoliths, siliceous, argillaceous, and calcareous rocks are all represented and each type is found to possess features of mineralogical and petrographic interest. Before giving an account of the petrology of the whole Haddo Mass, the writer proposes to describe certain xenoliths that consist mainly of corundum and spinel.

These corundum-spinel xenoliths were obtained from an old

[1] H. H. Read, " The Petrology of the Arnage District in Aberdeenshire," *Q.J.G.S.*, lxxix, 1923, 447.

[2] H. H. Read, " The Igneous and Metamorphic History of Cromar, Deeside, Aberdeenshire," *Trans. Roy. Soc. Edin.*, lv, 1927, 351.

[3] J. S. G. Wilson, " Explanation of Sheet 87," *Mem. Geol. Surv. Scot.*, 1886, 16.

quarry 300 yards south-east of Mill of Schivas, where the exposure shows a coarse norite with abundant xenoliths. The largest corundum-bearing xenolith was about a foot long by six inches broad and 2 inches thick, but the usual size is not greater than an inch or so in any dimension.

2. Petrography.

(*a*) Certain small xenoliths of this group are rusty-coloured rocks composed of corundum, spinel, and magnetite. In slice (Fig. 1*a*) corundum occurs as colourless euhedral or subhedral prismatic crystals with a maximum length of 1 mm. In many cases it is altered into a micaceous product in which irregular relics of the fresh mineral persist. The crystals show a fairly good alignment. The spinel, a dark green pleonaste, forms grains often

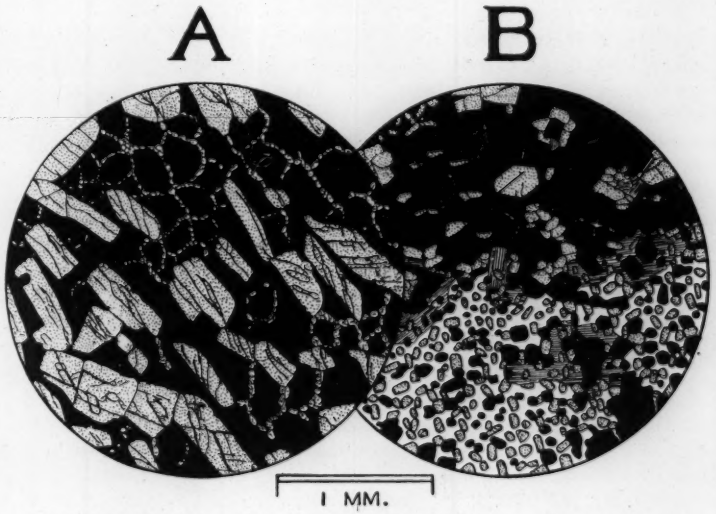


Fig. 1.—Corundum-spinel xenoliths, Haddo House, Aberdeenshire.
A. Corundum-spinel-magnetite-rock.
B. Corundum-spinel-biotite-cordierite-andesine-magnetite-rock.
Corundum, stippled; spinel (magnetite), black; biotite, lined; andesine and cordierite, unornamented.

separated from one another by rims of tiny corundum granules. Magnetite is the third and quite subordinate component. It builds shapeless grains usually wedged between adjacent corundum crystals. The specific gravity of the rock is 3·3–3·4, a value which would be considerably increased if no alteration of the corundum to micas had taken place. An estimation of the amount of corundum gives 36 per cent by weight, whilst that of magnetite is not more than 4 per cent. From these figures and an analysis

of a pleonaste from an exactly similar rock given by G. S. Rogers[1] (see after), it may be suggested that the composition of this emery xenolith is roughly 75 per cent alumina, 16·6 per cent iron-oxides and 8·4 per cent magnesia.

(*b*) The larger xenoliths of this group contain biotite, cordierite, and plagioclase in addition to the constituents of the emery just described. They are lustrous black hornfelses showing glistening mica flakes. An average specific gravity is 3·34; for comparison the following specific gravities are quoted[2]: gneiss, 2·60–2·80; mica-schist, 2·75–3·10; argillite, 2·4–2·80.

In thin sections[3] the dominant components are seen to be spinel and corundum; quite subordinate are biotite, plagioclase, cordierite, and iron-ore. The spinel is dark-green and quite fresh; it forms subhedral or rounded grains of a maximum diameter of 0·4 mm. Corundum builds euhedral prismatic crystals of a maximum length of 0·3 mm.; it is colourless in slice, but crushed fragments show a patchy blue to colourless pleochroism. Biotite occurs in large plates, 2–3 mm. across; it has X pale yellow, Y and Z deep reddish-brown, and is practically uniaxial. The fresh plagioclase, a basic andesine, forms plates 1–2 mm. across. Fresh cordierite with magnificent pleochroic haloes has the same habit as the felspar. Iron-ore occurs as small grains.

In structure, these rocks are characterized by a kind of cellular arrangement produced by the occurrence of large spinels in clusters and strings at the borders of felspar and cordierite grains or mica plates, all of which are crowded with smaller spinels and corundum crystals. Throughout the rock the minor constituents, biotite, cordierite, and felspar, act as groundmass-crystals in which lie spinel and corundum (Fig. 1*b*).

In consequence of the variation in mineralogical composition in different fields of the thin sections, it is impossible to give by measurement a complete estimation of the total mineralogical content. Measurements of four fields bring out these variations, the proportions being by volumes.

Field.	1	2	3	4	Average.
Spinel . .	47·2	51·3	80·1	27·0	51·4
Corundum . .	31·7	10·3	10·2	45·7	24·5
Biotite . .	13·5	—	—	—	3·4
Felspar and cordierite .	7·5	38·3	—	27·3	18·3
Magnetite . .	—	—	9·7	—	2·4

[1] G. S. Rogers, "Geology of the Cortlandt Series and its Emery Deposits," *Annals N. Y. Acad. Sci.*, xxi, 1911, 69.

[2] R. A. Daly, *Igneous Rocks and Their Origin*, 1914, 202.

[3] The writer wishes to express his indebtedness to Mr. P. J. Robinson, of Hamilton, who kindly made beautifully thin sections of these difficult rocks. Mr. Robinson's method is summarized in the forthcoming part of the *Transactions of the Geological Society of Glasgow*.

A partial analysis (total determined, 95·46%) of a rock of this group is given in column A of the table below.

	A	B	C	D	E	F	G
SiO_2	13·60	18·24	5·87	1·93	10·60	12·2	—
Al_2O_3	62·80	40·59	45·98	68·14	43·72	63·3	75·0
Fe_2O_3	1·81	9·12	26·03	1·43	13·75	15·2	} 16·6
FeO	10·96	12·14	4·85	16·25	20·11	—	
MgO	6·29	6·54	5·87	10·02	8·59	—	8·4
CaO	—	1·16	—	tr.	0·08	—	—
Na_2O	—	1·19	0·33	tr.	0·56	—	—
K_2O	—	0·62	0·16	tr.	0·52	—	—
H_2O+	—	5·02	4·44	1·15	0·85	—	—
H_2O-	—	0·48	0·35	0·12	0·07	—	—
CO_2	—	0·23	—	—	—	—	—
TiO_2	—	2·85	2·38	1·41	1·43	9·4	—
P_2O_5	—	—	0·11	tr.	tr.	—	—
SO_3	—	0·21	0·18	(S,0·05)	(S,0·07)	—	—
MnO	—	1·70	3·20	tr.	0·10	—	—
Cr_2O_3	—	—	—	0·04	0·06	—	—

A. Corundum-spinel-biotite-cordierite-andesine-magnetite xenolith, Haddo House, Aberdeenshire. *Anal.*, W. H. Herdsman.
B. Banded Hornfels, Laudenau, Odenwald. *Anal.*, Groebe.
C. Banded Hornfels, Laudenau, Odenwald. *Anal.*, Groebe.
D. Spinel Emery (High Grade), Buckbee Mine, Peekskill, N.Y. *Anal.*, G. S. Rogers.
E. Felspathic Emery, Salt Hill, Peekskill, N.Y. *Anal.*, G. S. Rogers.
F. Irish Bauxite, Lyles Hill, Antrim, recalculated as water-free, from an analysis given in C. S. Fox. *Bauxite*, 1927, 155.
G. Suggested composition of spinel-corundum-magnetite-rock, Haddo House, Aberdeenshire.

In addition to these corundum-spinel xenoliths just described there are many other silica-poor spinel-hornfelses occurring as xenoliths in the Haddo House norites. These are characterized by the following mineral assemblages : sillimanite-cordierite-spinel ; sillimanite - cordierite - spinel - plagioclase ; cordierite - spinel - plagioclase ; spinel-plagioclase-biotite.

3. Classification.

The rocks described here fall readily into their places in the classification of the silica-poor members of the argillaceous-calcareous group of hornfelses. This classification has been elaborated by C. E. Tilley.[1] It may be derived from that of the free-silica hornfelses instituted by V. M. Goldschmidt [2] by consideration of the two equations :—

andalusite (sillimanite) = corundum + quartz.
cordierite = 2 spinel + 5 quartz.

The Haddo House corundum-spinel-rock described first falls into

[1] C. E. Tilley, "Contact-Metamorphism in the Comrie Area of the Perthshire Highlands," *Q.J.G.S.*, lxxx, 1924, 41–2.

[2] V. M. Goldschmidt, "Die Kontaktmetamorphose im Kristianiagebiet," *Videnskr. Selsk. Skrift. Kristiania*, 1911, No. I, 140.

Tilley's Class 1 (*d*), corundum-spinel-hornfels. It represents the end-type theoretically derivable by desilication of an andalusite-cordierite-hornfels. The second group of Haddo House xenoliths, the corundum-spinel-plagioclase-biotite-cordierite-rocks, belong to Tilley's Class 2 (*c*).

4. Comparisons.

Occurrences of rocks essentially similar to the Haddo House corundum-spinel-rocks are, so far as the writer can judge, distinctly limited. Scrutiny of the accounts of these few occurrences reveals considerable divergences of opinion concerning their genesis. It will be profitable, therefore, to give the leading features of these occurrences and of the interpretations that have been advanced to explain them.

Sapphire-spinel-rocks, occurring as xenolithic masses, have been described from the hypersthene-gabbro ring-dyke of the Ardnamurchan Tertiary complex of the west of Scotland. H. H. Thomas [1] concludes that transference of material into the xenolith from the surrounding gabbro has been of very limited extent, and that the xenoliths have their original composition unaltered. As the original sediment from which these xenoliths were derived, Thomas suggests a highly aluminous and ferruginous deposit such as a bole, produced by lateritic decay of the basic lavas of the district.

The well-known sapphire-bearing xenoliths occurring in the tholeiitic sills of Carsaig in Mull have also been exhaustively dealt with by H. H. Thomas.[2] These accidental xenoliths show an interior of sillimanite-buchite and an outer zone of anorthite-corundum-spinel-rock. This outer zone resembles the Haddo House rocks. It is interpreted by Thomas as a hybrid rock due to the transference of magnesia and iron-oxide into material that had the composition of a highly aluminous fireclay, this uncontaminated material now being represented by the sillimanite-buchite. The basal Tertiary mudstone, believed to have been formed by the lateritic decay of basaltic ash, is suggested as the source of this material.[3] The present writer wishes to recall that in addition to the accidental xenoliths, the tholeiitic sills contain abundant cognate xenoliths markedly noritic in character.

G. Klemm [4] has described corundum-bearing and emery-like rocks found as xenoliths in the diorite of Reichelsheim in the Odenwald ; the associated xenoliths recall the other spinel-hornfelses occurring with the Haddo House rocks. Analyses (B and C) of

[1] H. H. Thomas, *Ardnamurchan Memoir*, 1930, 233–5, and 51, 71, 103, 104, 107, 108, 109.

[2] H. H. Thomas, *Mull Memoir*, 1924, 268–78, and "Certain Xenolithic Tertiary Minor Intrusions in the Island of Mull (Argyllshire)," *Q.J.G.S.*, lxxviii, 1922, 229–60.

[3] E. B. Bailey, G. V. Wilson, *Mull Memoir*, 53, 54, 59.

[4] G. Klemm, *Notizb. d. Ver. für Erdk. Darmstadt*, v Folge, i Heft, 1916, 23.

the two rocks poorest in silica of the series are given in the table on p. 449. Klemm considers the whole series of silica-poor hornfelses (no silica percentage exceeds 40) to be derived from laterites mixed with sand and with weathering products of adjacent amphibolites, etc. Similar corundum-bearing rocks occur in the gabbro of Frankenstein in the Odenwald; E. Kalkovsky considered these to be "aluminocratic schlieren", but Klemm [1] has argued that they are sedimentary xenoliths similar in origin to those of Reichelsheim.

Certain masses, dominantly of spinel and corundum, occurring in the diorite and norite of Klausen in South Tyrol, appear to show marked resemblances to the Haddo rock. F. Teller and C. von John [2] consider that the material of these alumina-rich masses was formed in the aureole, thence transported in solution into the igneous rock and there aggregated. Again, hercynite-bearing bands and enclaves have been described from the diorite [3] and gabbro [4] of the Upper Veltlin.

The well-known emery xenoliths found in the Cortlandt Series of Peekskill, New York, present remarkable similarities to those described here. This can be readily seen by comparing the descriptions and figures in the two cases.[5] It may be recalled that the Peekskill xenoliths are associated with others of unquestionable sedimentary origin and that their immediately enclosing rock is a norite proper. They have been interpreted in various ways. G. H. Williams considered them at first to be segregations in the norite,[6] but afterwards regarded them as essentially of thermal metamorphic origin.[7] J. H. Pratt [8] appears to endorse Williams' first view and believes the emery to be due to segregation along the borders of the norite body. Later detailed study of the Peekskill occurrences led G. S. Rogers [9] to interpret them in the light of Morozewicz's experiments on artificial melts. In view of the richness of these xenoliths in alumina, Rogers postulated some kind of segregational process, but concluded that the emery had been formed by the action of the igneous rock upon included sedimentary material, "thus giving rise to a magma supersaturated with respect to iron and alumina and out of this the corundum and its associates crystallized according to the laws formulated by Morozewicz.[10]

[1] G. Klemm, ibid., 37, and iv Folge, xxxv Heft, 1914, 5.
[2] F. Teller and C. von John, *Jahrb. d. k. k. Geol. Reichsanst.*, xxxii, 1882, 589.
[3] W. Rasch, *Neues Jahrb., B.-Bd.*, xxxii, 1911, 232.
[4] G. Linck, *Sitz.-Ber. d. k. preuss. Akad. Wiss. zu Berlin*, i, 1893, 47–53.
[5] G. S. Rogers, loc. cit., 68–9.
[6] G. H. Williams, "Norites of the Cortlandt Series," *A.J.S.*, **3**, xxxiii, 1887, 135, 191.
[7] G. H. Williams, "Contact Metamorphism produced in the adjoining Mica Schist and Limestone by the Rocks of the Cortlandt Series," ibid., xxxvi, 1888, 254.
[8] J. H. Pratt, *Bull. U.S.G.S.*, No. 269, 1906, 93.
[9] G. S. Rogers, loc. cit.
[10] G. S. Rogers, loc. cit., 84.

The beautiful corundum-sillimanite-rock found in the norite of the Bushveld and described by A. L. Hall and L. T. Nel [1] shows a narrow pleonaste-rich border which presents many points of resemblance to the Haddo House xenoliths. This spinel layer is interpreted as a kind of reaction rim, surplus alumina of the sedimentary xenolith combining with magnesia and iron-oxide of the magma.

5. Discussion.

A review of the accounts of corundum-spinel xenoliths just summarized reveals considerable divergences of opinion concerning their origin.

It seems certain that these emery masses are not aluminocratic schlieren or magmatic segregations. They are of an origin in which sedimentary rocks are fundamentally concerned. They have the habit of true accidental xenoliths and sometimes show, as in Mull and South Africa, definitely sedimentary interiors. They are the silica-poorest members of a large series of silica-poor xenoliths, innumerable representatives of this series being recorded from most of the localities.

Since these xenoliths are of sedimentary origin their original character may be considered. Two divergent views have been expressed. In the first of these, the xenoliths are believed to have preserved their original composition unchanged. For instance, Klemm for the Odenwald examples suggests as the initial sediment a laterite mixed with sand and the weathering products of adjacent amphibolites. Such a climatic conjunction appears to the present writer to be extremely unlikely. Again, Thomas for the Ardnamurchan cases also regards the initial composition to be unchanged, and considers as a possible source boles formed by the lateritic decay of basic lavas. These emery xenoliths, however, differ from dehydrated bauxites in their high magnesia content, as is seen from comparison with the recalculated analysis of a typical Irish bauxite given in the table on p. 449. Magnesia in almost all bauxites reaches only a fraction of 1 per cent. The Tertiary basal mudstone in which lateritic decay is believed to have operated contains only 0·34 per cent magnesia.[2] The concentration of alumina in the laterite-forming process is not accompanied by a concentration of magnesia, a fact recognized by Klemm in his explanation summarized above.

The second group of explanations of emery xenoliths suggests some form of contamination or transfer as the mode of operation. For instance, Thomas explains the formation of the Mull spinel-corundum border as due to transfer of magnesia and iron-oxide

[1] A. L. Hall and L. T. Nel, "On an Occurrence of Corundum-sillimanite Rock in the Norite of the Bushveld Igneous Complex west of Lydenburg," *Trans. Geol. Soc. S. Africa*, xxix, 1926, 1.

[2] *Mull Memoir*, 34.

from the magma, and Hall and Nel favour a similar process for the production of the South African pleonaste border to the corundum-sillimanite rock. Rogers in the case of the Cortlandt rocks regards contamination of the original magma with alumina as the effective process.

Consideration of the nature of the igneous rocks in which emery xenoliths are found leads at once to results of genetic significance. These xenoliths all occur in basic rocks. In most cases, e.g. Haddo House, Cortlandt, Bushveld, Klausen, the enclosing rocks are definitely noritic ; in the cases of the Odenwald and Upper Veltlin the igneous rocks are called diorite or gabbro. This noritic cast is surprisingly clearly revealed in the two Scottish Tertiary examples, Ardnamurchan and Mull. The former xenoliths occur in hypersthene-gabbro. Apart from its occurrence in this rock, orthopyroxene is a somewhat rare component of the Tertiary igneous rocks of the district. The Mull xenoliths appear at first sight to be an exception to the rule being developed here, since they are found in tholeiite-andesite sills. Examination of H. H. Thomas' account shows, however, that the production of the sapphire xenoliths and of their spinel-corundum borders took place at a lower level before they were enclosed in the tholeiitic magma. *But the tholeiite sills contain innumerable cognate xenoliths of markedly noritic character*, so that it is a fair conclusion to suggest that the sapphire-spinel accidental xenoliths and the noritic cognate xenoliths were once in intimate association.

The association of emery xenoliths and noritic rocks developed in this paper finds its explanation in the work of N. L. Bowen.[1] In his discussion of the effects of basaltic magma on aluminous sediments, Bowen deduces that the first result would be to pile up the alumina in the xenolith with the production of such minerals as sillimanite, etc. The addition of this alumina-rich material to the basic magma would result in the increase of the amount of magnesia in the pyroxene and of anorthite in the plagioclase, that is, in the production of a norite. If there were not so many slates there would not be so many norites. The spinel-rich xenoliths and borders represent the reaction between magma and inclusion arrested midway.[2] Bowen has applied this mechanism to the Cortlandt emery deposits and, as shown in this paper, it appears to apply to all occurrences of spinel-corundum xenoliths.

[1] N. L. Bowen, *The Evolution of the Igneous Rocks*, 1928, chapter x.
[2] N. L. Bowen, ibid., 212.

The Genetic Relationships of Pegmatites, Aplites, and Tin Veins.[1]

By D. R. Derry.

(PLATES XV–XVII.)

Introduction.
Common Pegmatites and Aplites.
Pegmatite and aplite in distinct dykes.
Dykes containing both pegmatitic and aplitic material.
Discussion of observations.
Complex Pegmatites and Aplites.
General geology of the Winnipeg River area.
Form and mineral distribution of the pegmatites.
Pegmatites containing cassiterite.
Albite aplites containing cassiterite.
Pegmatites containing lithium minerals.
Pegmatites containing beryl and tantalite.
Paragenesis.
Texture.
Conclusions.
Summary.
The relationship of tin-bearing pegmatites to tin veins.

INTRODUCTION.

THE complex pegmatite dykes, containing rare minerals in relative abundance and often in huge crystals, have for many years been a subject of much interest both from an economic and a scientific point of view. Of recent years it has been felt, particularly by American geologists, who have had more opportunity to study these occurrences, that the previously-held conceptions regarding the origin of such rocks are not altogether satisfactory. It had been assumed that the concentration of rare elements and the growth of huge crystals is brought about merely by the fluidity of the magma due to the presence of volatile elements, the minerals crystallizing out as in an ordinary plutonic rock. Opposed to this old conception is the hypothesis published independently but almost simultaneously by Schaller (1)[2] and Hess (2) though suggested earlier by Larsen. The essence of this new hypothesis is that the large crystals in pegmatites, in particular those of uncommon minerals, are produced, not by direct crystallization from a magma, but by replacement of the original material of the dyke by the action of magmatic solutions. Such a suggestion has an important bearing not only on the differences in origin of pegmatites and aplites but on their relation to tin veins with which they often seem to be associated.

In Canada interest in these complex[3] pegmatites was recently

[1] A synopsis of a thesis presented as part of the requirements for the degree of Doctor of Philosophy at the University of Toronto.

[2] Numbers in parentheses refer to bibliography at end.

[3] The word "complex" is applied to those pegmatites containing a significant proportion of minerals other than the potash felspar, quartz, and micas of common pegmatites.

renewed by the discovery in eastern Manitoba of a number of these bodies, some of which contain tin, lithium, tantalum, beryllium, and other rare elements. The problem undertaken by the writer was to learn something of the origin of these interesting occurrences and in particular to see whether the new replacement hypothesis seemed to be applicable in this district. One of the more important features noted was the sharp contrast between very coarse and very fine-grained or aplitic material in the same dyke or sill. The presence of aplitic material in complex pegmatites is thought by the writer to be of the greatest importance in a discussion on their origin and to have been somewhat neglected in much of the literature on this subject.

Before attempting to understand the origin of pegmatitic and aplitic material in these complex dykes and sills it is necessary for the investigator to have come to some conclusion regarding the reasons underlying the difference between *common* pegmatite and aplite, in which rare elements are absent or insignificant. An opportunity for studying a large number of such common pegmatites and aplites was afforded to the writer during the summer of 1930 when he was undertaking a reconnaissance geological survey along a ninety mile stretch of the Inter-provincial boundary between Ontario and Manitoba for the Ontario Department of Mines. A summary of these observations will be given before going on to the more complicated conditions in the pegmatites containing rare minerals.

COMMON PEGMATITES AND APLITES.

The region where the relations of common pegmatites and aplites were studied is in the vicinity of the Ontario-Manitoba boundary line between north latitudes 53° and 54°. The geology is typical of a great part of the Canadian Precambrian shield, consisting of large areas of granitic rocks varied with narrow roof-pendants of an older series of sedimentary-volcanic rocks of probable Keewatin age. The dykes of pegmatite and aplite represent the last stage of intrusive activity. They cut the sedimentary-volcanic series, but are more abundant in the intermediate granites and granodiorites, especially in those parts which have apparently solidified near the roof of the batholith. The particular composition of the intrusive acting as host seems to exercise little or no influence on the mineral composition of the pegmatitic oraplitic injections. In both pegmatites and aplites the minerals seem to be almost always microcline (sometimes orthoclase), quartz, and a variable proportion of mica. On the whole, the pegmatites are commoner than the aplites, but no particular intrusive mass is noticeably richer in one to the exclusion of the other.

The observations on the relationships of the pegmatites to the aplites fall into two classes: (1) Cases where pegmatites and aplites

form separate and distinct dykes or veins cutting each other, and (2) cases where one dyke carries both pegmatitic and aplitic material.

(1) Pegmatite and Aplite in Distinct Dykes.

In a large number of places a regular intrusive series of dykes and veins may be distinguished. In such cases each successive intrusion, either massive or in dykes, is more acid and finer in grain than the preceding one, until a pink aplite is reached. Following

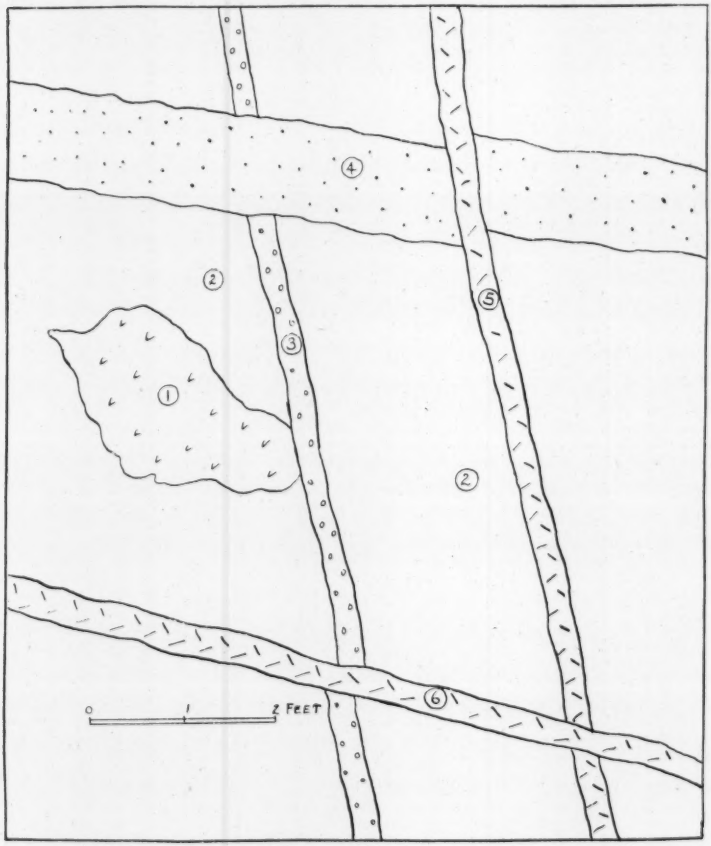


Fig. 1.—Surface outcrop showing intrusive succession. (1), Granodiorite, (2) Grey hornblende-granite, (3) Grey aplitic granite, (4) Pink aplite, (5) Pegmatite (first set), (6) Pegmatite (second set). Poplar river, Manitoba.

the aplite is pegmatite in dykes or veins cutting sharply across those of aplite (Fig. 1). Thus there has been a sharp change either in conditions or in material between the injection of the last aplite and the first pegmatite.

In a few occurrences the order of intrusion was seen to depart from the general rule. In one case where the country rock consists of porphyritic diorite the intrusive dykes consist, in chronological order, of (*a*) grey hornblende—granite, (*b*) veins of quartz containing a variable proportion of microcline, thus grading from true quartz veins to pegmatites, (*c*) pink aplite (*d*) pegmatite in small stringers cutting all the above types. Thus this series varies from the commoner case in having quartz-pegmatite veins intermediate in age between the grey granite and the aplite. The sharp contrast in grain and the absence of gradational types, however, is again noticeable.

(2) Dykes Containing both Pegmatitic and Aplitic Material.

Dykes of this type show a great deal of variation in the relations of the fine to the coarse-textured material (Fig. 2). The observed features may be grouped as follows : (*a*) Dykes of aplite with sharply demarkated borders of pegmatite, (*b*) Dykes of aplite containing stringers of pegmatite, (*c*) Dykes of pegmatite with borders of finer material, almost aplitic, (*d*) Dykes of aplite with a small proportion of pegmatitic material, sharply demarcated in texture, but forming irregular segregations or stringers within the dyke.

Discussion of Observations.

The earlier age of aplite than pegmatite dykes is by no means universal, though it is the general rule for this particular district. Thus Miller (3), in an excellent description and discussion of the aplites and pegmatites of New York State, notes that the first pegmatites are earlier than the first aplites, but a second series of pegmatites is later than, and cuts, the aplites. Miller stresses the fact that the earlier pegmatites were squeezed into their present positions before the surrounding rocks had completely solidified. Spurr (4) also notes aplites cutting pegmatites in an area in Manitoba. One common characteristic to all these occurrences, however, is the sharp distinction in texture between the two types of dykes.

In the cases where pegmatitic and aplitic material occur in the same dyke, here again the sharp distinction between coarse and fine material is almost always apparent. Cases where gradation in texture occurs are rare and may be regarded as incomplete stages in a process that produced the two extremes, pegmatite and aplite.

If it were the rule that acid rocks were consistently coarser at successfully later stages of intrusion, a fairly simple explanation could be applied. The process of differentiation by progressive crystallization tends to concentrate water and other volatile substances in the " rest-magma ". These volatiles would allow greater mobility and molecular diffusion, facilitating the development of large crystals. Such a process, however, does not take place. After the stage of massive acid granite the paths diverge, giving

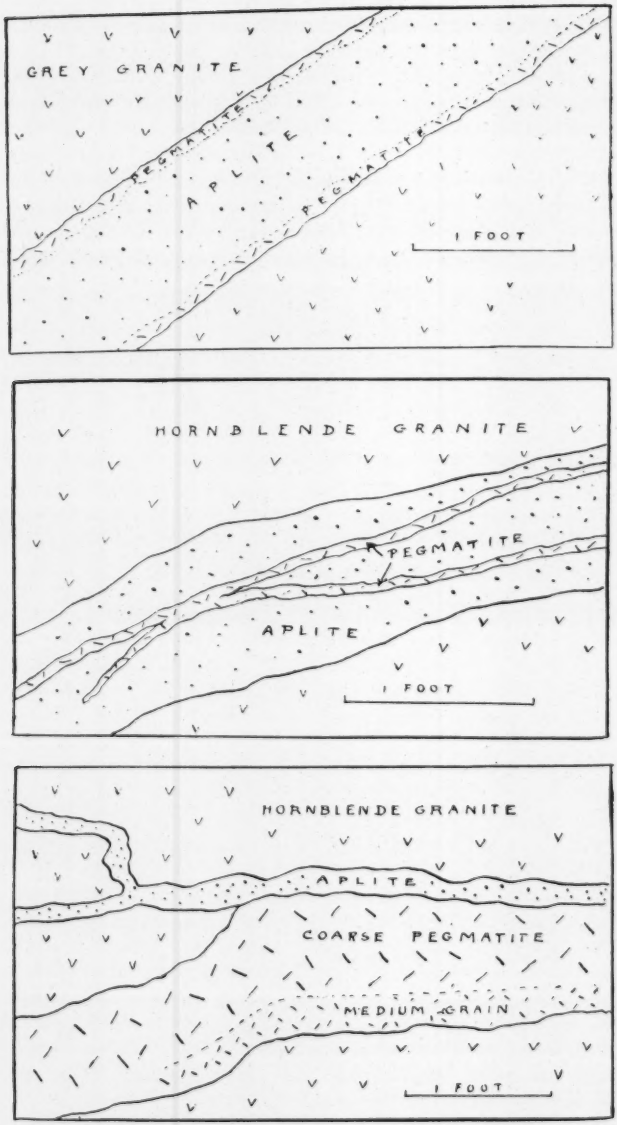


FIG. 2.—Sketches of surface outcrops showing three examples of the different relationships found between pegmatitic and aplitic material when present in the same dyke. Ontario-Manitoba boundary.

rise to increasingly fine crystallization on the one hand and increasingly coarse on the other. That most of the water present follows one path and forsakes the other seems to be a reasonable, if not necessary, conclusion, since the minerals of both classes are the same, so far as the dykes in the granite areas under discussion are concerned. What is it that causes the separation of water from one part of the residual magma and adds it to the other ? The study of physical chemistry fails to reveal reasons for a sharp separation of this sort. It is possible that the theory of squeezing of a partially crystallized magma, as suggested by Barrow (5), Harker (6), and Bowen (7) for various classes of differentiation is applicable here. Thus the magma giving rise to aplites may represent the crystallized part, or " crystal mesh " as Bowen terms it, which has been deprived of much of its water and the rick-forming material still in solution, due to squeezing by later movements of the batholithic mass. In this way the closely-packed crystal mesh and the expelled liquid might form two distinct masses. A relief of pressure by further movements while the temperature was still high would result in the remelting of the closely-packed crystal mesh, which would then be in a state to be tapped to fill fissures in the overlying granitic masses. The final solidification would be aplitic, due to the lack of water with increased viscosity and therefore decreased molecular diffusion. The liquid portion squeezed out may be forced into localized spots of lower pressure and there imprisoned until similarly tapped, during the cooling and settling of the batholith, to form pegmatitic injections. If the pegmatitic and aplitic magmas occupy separate reservoirs for the above reasons, the priority of the one type of dykes over the other might depend on local conditions in the cooling and contraction, with resultant fissuring, in the overlying solidified granite.

The squeezing process, if it is a fact, might also prevail at later stages after the aplitic material has been injected into the fissures in which it is now found. Squeezing during the final crystallization could result in the last dregs of liquid material being separated. This final separation may account for the small stringers or patches of pegmatitic material which fill cracks in some aplite dykes or replace portions of them. The earlier the squeezing had occurred the more distinct units would the aplite and pegmatite dykes be.

It has been suggested by Schaller (8) and Hess (9) that even the common quartz-microcline pegmatite is not the original material of the intrusion, but a replacement of an originally fine-grained orthoclase rock. Although, as shown later, the writer supports Schaller's theory for the formation of complex pegmatites, he could find no evidence to show that replacement had been an important factor in the production of the common pegmatites. It is true that such cases as aplite with pegmatite at the borders or as irregular stringers within the dyke may be replacement of aplite by later mobile pegmatitic solutions. Replacement has taken place to a

minor extent; but for the greater number of common pegmatite and aplite dykes, sharply cutting each other, a genetic difference due to earlier and more deep-seated separation of material is indicated.

COMPLEX PEGMATITES AND APLITES.

General Geology of the Winnipeg River Area.

The Winnipeg River area in eastern Manitoba possesses pegmatites of a complex nature, which, in their content of minerals containing tin, lithium, beryllium, and other rare elements, resemble the much-described pegmatites of South Dakota, Carolina, and California. The area lies approximately one hundred miles north-east of Winnipeg. Owing to recent commercial interest in the occurrences in this area many freshly-broken faces are available, which, together with the exposed ridges polished by glaciation, afford ideal opportunities for detailed examination. No commercial bodies of tin have so far been exposed, but some of the bodies of lithium minerals are promising from an economic standpoint. Other pegmatites may in future be worked for the felspar and the rare minerals together.

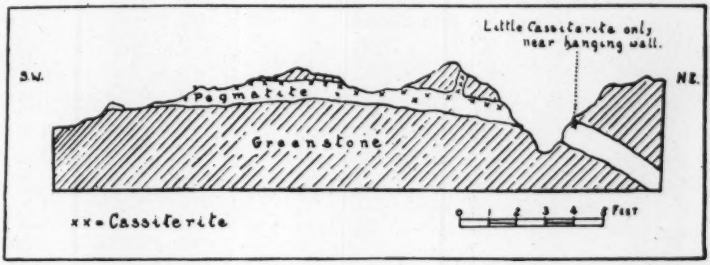
The geology of the Winnipeg River area has already been fully described by J. F. Wright (10), consequently no attempt will be made here to deal with the detailed petrology of the rocks as a whole. All the consolidated rocks are of Pre-Cambrian age and consist of a series of sedimentary and volcanic rocks, invaded and metamorphosed by a great plutonic series. The sediments include quartzite, greywacke, conglomerate, and schists, while the volcanic types comprise andesite, dacite, and trachyte. The intrusive series ranges from peridotite, through diorite, granodiorite and sodic granite to acid biotite granite. The order of intrusion seems to have been from basic to acid.

The last phase of igneous activity, closely associated with the acid granite, consisted of the injection of numerous dykes and sills of pegmatite and some of aplite. Many of these pegmatite dykes are of the common type containing only microcline (or orthoclase), quartz, and micas. Some of the dykes and sills, however, are of a complex nature, and it is these which have been studied in detail. They are found cutting both volcanic and sedimentary rocks. One characteristic is common to all those portions of dykes or sills seen to contain rare minerals: this is the presence of albite almost to the exclusion of potash felspar. It is interesting to note that the same characteristic has been noted by Bastin, Hess, Schaller, Wagner, and others in widely scattered districts.

The observations will be dealt with under three separate headings: (1) The form of the bodies and the arrangement of minerals or groups of minerals. (2) The paragenesis as interpreted from macroscopic and microscopic examination. (3) The texture, in particular the relationship of the coarse- to the fine-grained material.

Form and Mineral Distribution.

In general the pegmatite bodies are rather irregular in width and in direction. All variations between vertical dykes and flat or arched sills exist, but it is noticeable that those bodies richest in rare minerals generally take the form of flat-dipping sills. Irregular stocks, lenses, or funnel-shaped masses may also be found.



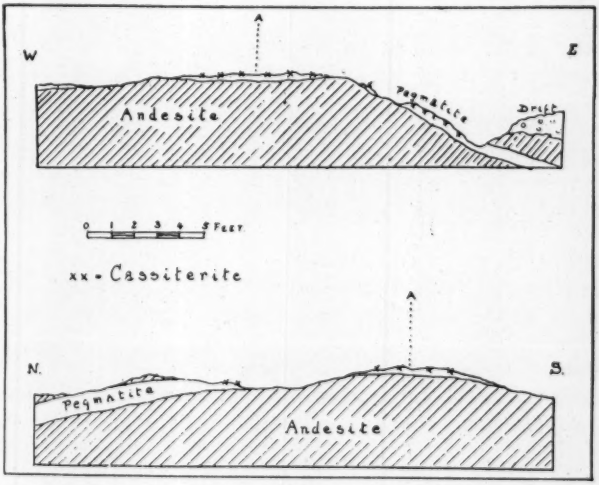


Fig. 3.—Vertical sections through two sills of tin-bearing pegmatite showing the tendency for cassiterite to be segregated in the uppermost parts of the bodies. Bernic Lake, Manitoba.

As a general rule those bodies containing an appreciable amount of cassiterite do not carry much lithium and vice versa. The two types will therefore be treated under separate headings.

Pegmatites containing Cassiterite.—Although economic quantities of cassiterite have not so far been exposed, the mineral has been

found in small, but relatively rich, segregations. In almost every case examined by the writer the cassiterite shows a preference for the hanging-wall side of a flat-dipping sill of pegmatite. No segregations were seen either near the footwall of a sill nor in any quantity in a vertical dyke, though a few scattered crystals might be found. A particularly favourable spot for cassiterite segregations seems to be near the apex of a shallow, arched sill, as may be observed in several occurrences round Bernic Lake (Fig. 3). When such sills are followed down the dip the cassiterite is found to decrease. The cassiterite is associated with white albite, quartz, black tourmaline, green muscovite, and sometimes garnet, spodumene, beryl, and apatite in small quantities. When traced laterally along the outcrop of the dyke or sill this mineral association is often seen to give place to common pegmatite containing only potash felspar, quartz, micas, and sometimes tourmaline.

Albite-Aplites containing Cassiterite.—The rock referred to as albite-aplite consists of fine-grained, white albite as its main constituent, with subordinate quartz (Plate XV, *b*). The rock often forms part of a dyke or sill, and in one case a dyke was seen to consist wholly of this material. Cassiterite does not form segregations in this type of material, but may occur as scattered crystals (Plate XV, *c*), so small as to be easily overlooked in the hand specimen.

Diamond drilling on the north shore of Bernic Lake has revealed a large sill-shaped body, 200 feet thick, which consists of albite-aplite with minute specks of cassiterite, and some large masses of quartz, in the upper two-thirds, while the lower third consists of coarse pegmatite made up of albite, quartz, tourmaline, and mica, but no cassiterite. A few miles north of Bernic Lake a dyke of albite-aplite contains small cassiterite crystals scattered all through it.

As will be shown later in discussing the microscopic relationships, the cassiterite in these occurrences must differ considerably in its method of deposition from that in the segregations in coarse pegmatite.

Pegmatites containing Lithium Minerals.—Like the tin-bearing pegmatites, those bodies containing lithium minerals generally take the form of flat-dipping sills rather than dykes. The lithium minerals found in significant quantities are spodumene, lepidolite, and, more rarely, amblygonite. In all the occurrences seen the lithium minerals show some fairly regular arrangement with respect to the walls of the body. In one type of occurrence the lower portion of the sill consists of albite and quartz, sometimes rather fine-grained, while the uppermost portion consists of material resembling common pegmatite, made up of quartz, red felspar, mica, and tourmaline. The red felspar, though resembling microcline in external appearance, is now fine-grained albite, which is thought, for reasons given later, to have replaced original microcline. Between these upper and lower portions is the central zone containing the lithium minerals, generally

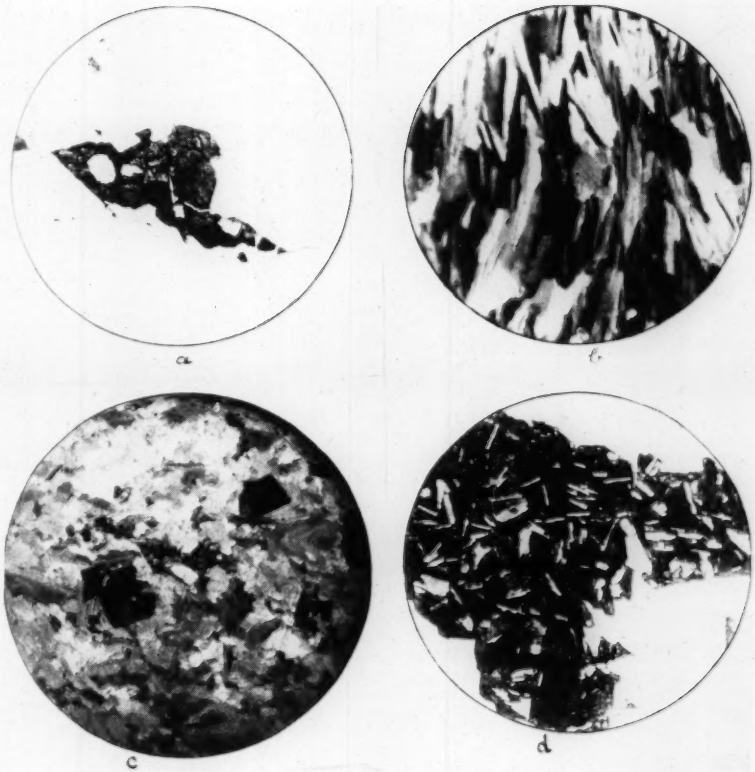


FIG.

a.—Cassiterite in albite in a complex pegmatite. The relationship suggests that the cassiterite has been deposited by replacement of the albite rather than by original crystallization. × 25.

b.—Albite-aplite showing the parallel arrangement sometimes assumed by the albite lamellae. Crossed nicols. × 40.

c.—Scattered cassiterite crystals in albite-aplite. Nicols at 70°. × 30.

d.—Cassiterite embedded in albite-aplite and containing inclusions of well-formed albite laths. × 32.

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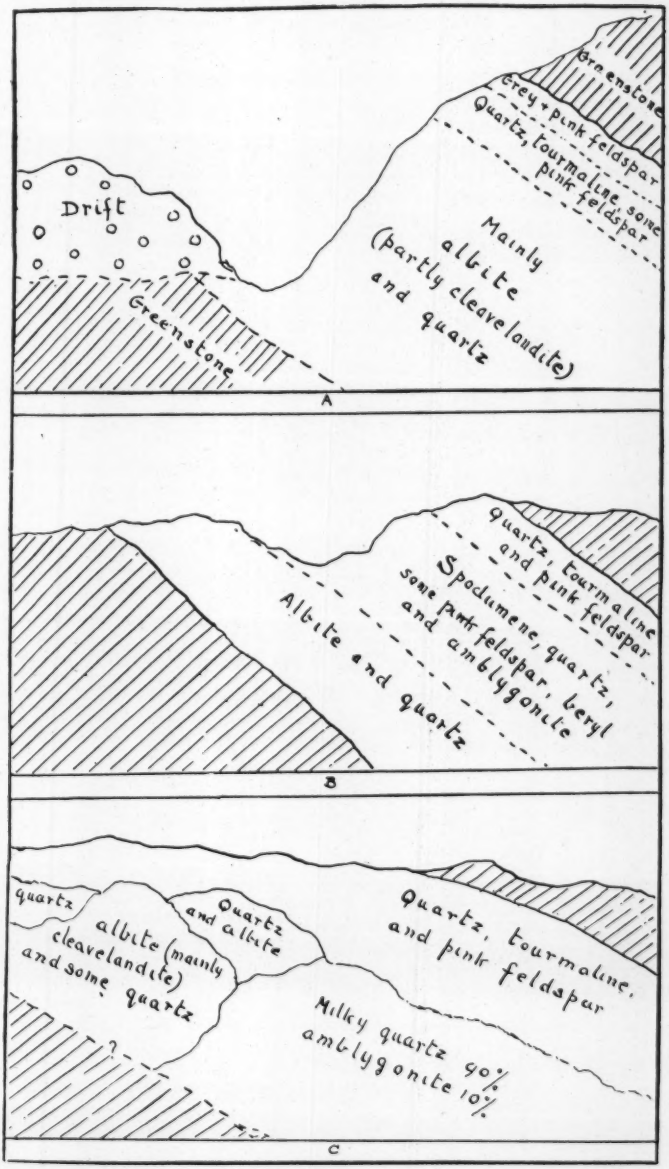


FIG. 4.—Three vertical sections through an inclined sill of complex pegmatite. A, Outcrop on north side of hill. B, At summit. C, Cliff face on south side. Bernic Lake, Manitoba.

embedded in quartz and albite. Fig. 4, showing three exposures in one sill, portrays a good example of this type of occurrence.

The most important lithium deposit in the area, that known as the Silverleaf, is of rather different character to the above types. The pegmatite body is funnel-shaped, the wall on the north-western, northern, and eastern sides dipping in towards the centre, while the

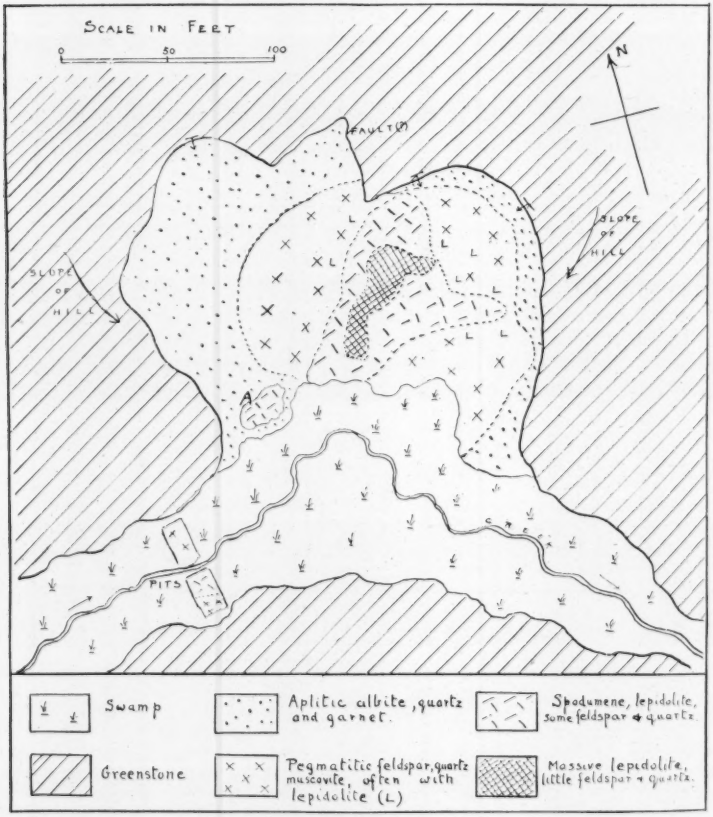


FIG. 5.—Sketch-map of the Silverleaf Lithium Deposit showing the general shape and the zoning of the pegmatite body.

whole body pitches towards the south-west. The widest part of the outcrop, on the side of a hill, is approximately 200 feet in diameter. A brief examination of the outcrop reveals a fairly distinct zonal arrangement of the different mineral associations (Fig. 5). The outer zone is a fine-grained red rock, almost aplitic, consisting of albite and quartz, with small garnets forming curved, roughly

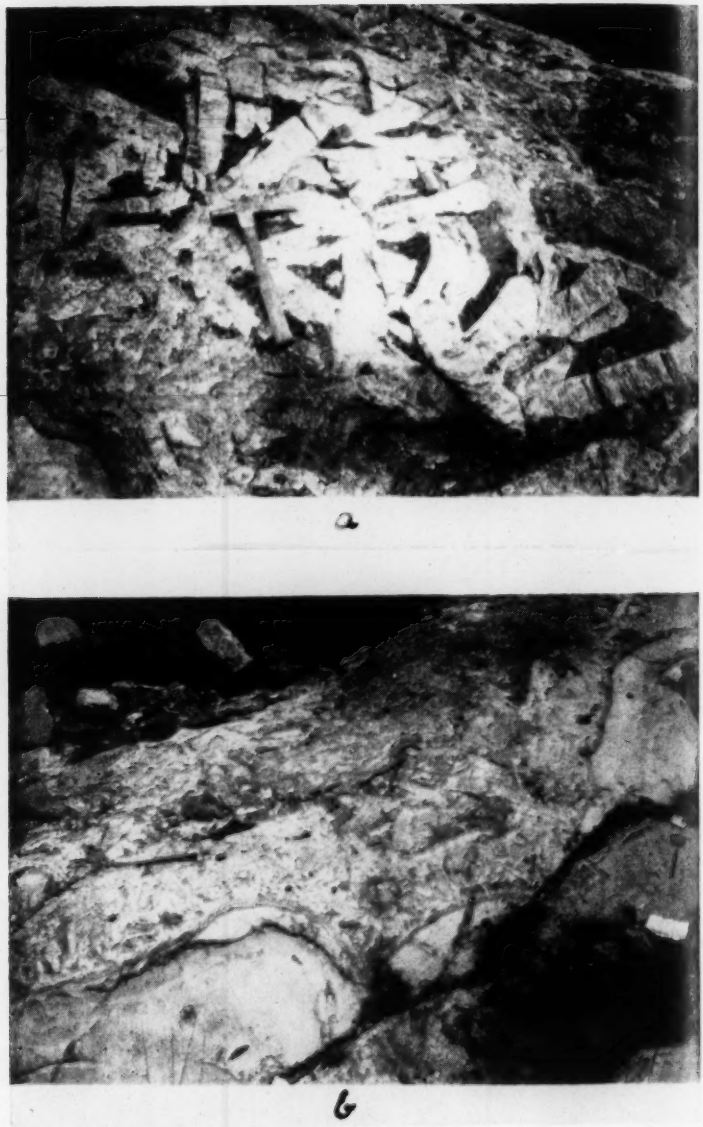


FIG.

a.—Large spodumene crystals set in purple lepidolite and some albite.

b.—View of the contact of the pink, faintly-banded aplite with the coarse phase of albite, lepidolite and spodumene.

Silverleaf Lithium Deposit, Manitoba.

To face p. 465.]

parallel lines. Next to this zone is coarse pegmatite containing microcline, partly replaced by albite (see later), quartz, muscovite, and some purple lepidolite forming nodules and veinlets in the felspar crystals and along the crystal boundaries. Inside this second zone is one characterized by spodumene in large crystals together with a little white albite and purple lepidolite (Plate XVI, *a*). Inside this zone and forming the core of this part of the body is a mass of nearly pure lepidolite, purple to grey in colour, and finer grained than that in the second zone. In the widest part of the body the three central zones are not separated by sharp contacts. In one place, however (A in Fig. 5), near the southern side of the body, the outer fine-grained zone is seen to be in sharp contact with the third zone (that rich in spodumene). The contact takes the form of a series of curves with their convex sides towards the coarse spodumene phase (Plate XVI, *b*). The fine-grained phase has bands of garnets in curved lines parallel to the curves of the contact. It is almost certain, therefore, that the fine-grained rock is the intrusive which formed the contact. However, the spodumene in the coarse phase shows a definite arrangement with regard to the contact. The crystals increase in size away from the contact and those nearest to it are arranged with their long axes normal to the contact. The spodumene rock cannot, therefore, have been the original country rock intruded by the aplite. The anomaly can best be explained by considering that the red aplite intruded some pre-existing rock, probably coarse common pegmatite, and that as the aplite solidified a pressure was exerted which squeezed the remaining liquid, which still contained the lithium compounds, into the adjoining country rock (probably common pegmatite). There the lithium minerals and some albite must have been deposited by replacement of the minerals of the pre-existing rock.

Pegmatites containing Beryl.—Beryl was not seen to occur in a very regular position with regard to the walls of the pegmatite bodies. White beryl in crystals about an inch in diameter is found sometimes in the lithium-rich pegmatites. The richest beryl occurrence so far exposed in the area, however, is green beryl, in large crystals, in an almost horizontal sill of pegmatite. The beryl crystals attain a length of 3 feet and tend to be arranged in groups radiating from a point. The surrounding material is red albite felspar.

Tantalite, arranged along cleavage cracks in the felspar, is found in the same sill. The tantalite has clearly come in after the felspar and by replacement of it, by solutions seeping along the cleavage cracks (Fig. 6).

Occasional crystals of uraninite and monazite are found in the same sill, embedded in albite.

Paragenesis.

It has been mentioned that all the pegmatites containing rare minerals are characterized by the predominance of albite over

microcline or orthoclase. It was also pointed out that the " complex " portion of a pegmatite can often be traced into common pegmatite containing only potash felspar, quartz, micas, and sometimes black tourmaline. When the place where the gradation takes place is studied carefully it is found that there is strong evidence that the albite has replaced original potash felspar. In the first stages the albite forms stringers through orthoclase (Plate XVII, *a*). Along the stringers at intervals nests or pockets occur where the twinned albite laths grow off into the surrounding orthoclase. Finally, in many cases, the whole of the orthoclase becomes replaced. One of the most perfect proofs of this replacement is seen in the case illustrated in Plate XVII, *c*. A large crystal, one of many, shows the external form of microcline or orthoclase, but the crystal is seen now

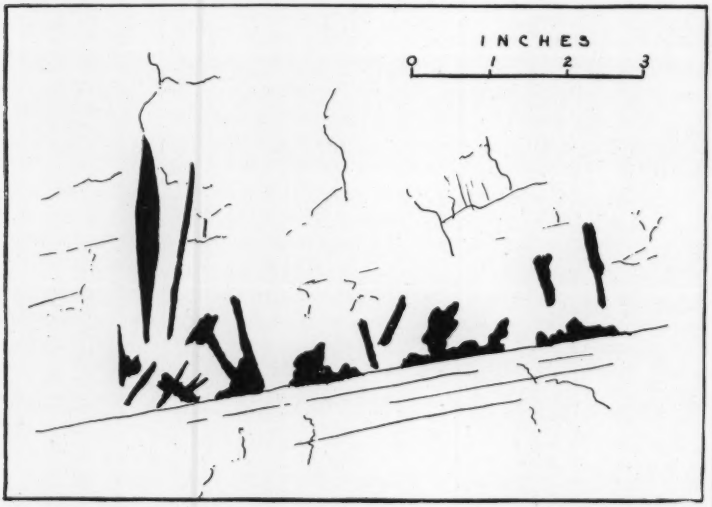
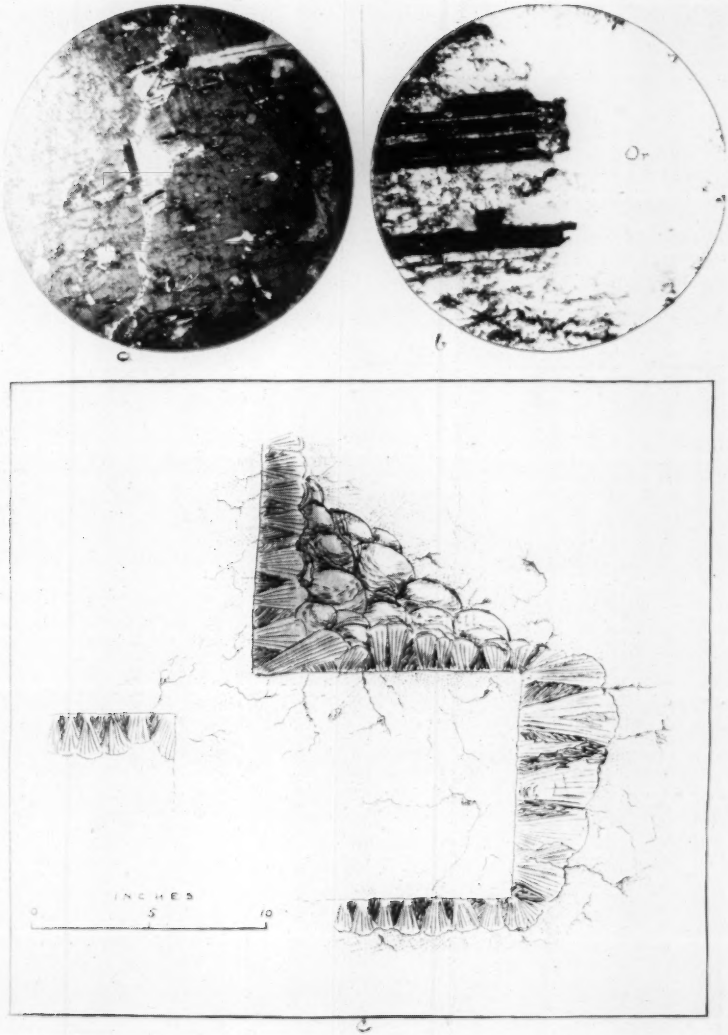


FIG. 6.—Face of pegmatite displaying tantalite (black) replacing red albite along cleavage cracks. Winnipeg river, Manitoba.

to be made up entirely of an interwoven mass of radiating albite lamellae. The lepidolite in the same example has been deposited also by replacement along the crystal boundaries of the felspar. Similar evidence of replacement of potash felspar by albite can be found in nearly every complex pegmatite.

Cassiterite, when studied in thin sections, is seen to form incomplete crystals, but showing some good faces. In some cases, however, minute stringers are seen to protrude from the cassiterite grain into the surrounding albite (Plate XV, Fig. *a*). Inclusions of albite are seen in some cassiterite grains. These features suggest that the cassiterite is not deposited as an early crystallizing mineral, but at a relatively late stage by replacement of the albite.



STAGES IN THE REPLACEMENT OF POTASH FELSPAR BY ALBITE.

FIG.

a.—Initial stage. Albite replacing orthoclase along a narrow stringer. Crossed nicols. × 15.

b.—Further stage showing albite growing by replacement of a single orthoclase crystal. Crossed nicols. × 40.

c.—Final stage. Large crystals having the external shape of orthoclase or microcline, now composed entirely of radiating lamellae of albite. Lepidolite (dark), also with a radiating structure, has replaced the felspar along crystal boundaries.

[*To face p.* 466.

The cassiterite in albite-aplites shows rather different characteristics The grains are small and irregular and often contain numerous perfectly-formed albite laths (Plate XV, *d*). It seems unlikely that albite could have the power to replace an insoluble mineral like cassiterite and form perfect crystals in it. On the other hand, if the cassiterite replaced the albite, the included material should show corroded boundaries instead of sharp edges. It seems probable that in the case of the albite-aplites, albite has started to crystallize out, but has been interrupted by the precipitation of cassiterite, which formed round the laths of albite. Further crystallization of albite then surrounded the cassiterite.

Lepidolite seems to be definitely later than albite. It forms stringers and nodules in the latter and is never cut by albite stringers.

Spodumene forms good crystals in the albite and is never seen to be attacked by the latter. The abundant cleavage cracks offer ample opportunity for filling or replacement by later material, but the only material so filling these cracks is quartz. It seems probable, therefore, that the spodumene has grown by replacement of the surrounding albite and was one of the last minerals to form. The position of amblygonite in the paragenesis is less certain, but the field relationships suggest that its age is near to that of spodumene.

Tantalite has definitely formed later than the albite and by replacement of it, as was shown in the description above. The plate-shaped crystals growing off into the felspar and arranged along cleavage cracks leave no doubt as to the late age of tantalite and the deposition by replacement.

The position of beryl in the paragenesis is rather uncertain. The radiating groups of large crystals could not have grown in a liquid ; they must have grown by replacement of some solid material or else in a very viscous mass. This feature suggests an age later than the felspar of the pegmatite. In one case, however, where a small beryl crystal was broken, the break had been filled with albite. It is possible that the beryl replaced original potash felspar and after being broken was healed up with albite at the same time as the albitization of the potash felspar.

Tourmaline occurs in two distinct types : the common black iron-rich variety and a coloured type, pink or green, which probably contains lithium, resembling the gem tourmaline of California. The latter type is rare, but when present forms radiating clusters cutting through the albite. Its position in the time scale is thought to be late, probably near to spodumene. The black, iron-rich tourmaline, on the other hand, is one of the earliest minerals to form. When surrounded by albite the tourmaline prisms show decidedly corroded borders. It is suggested that the black tourmaline in complex pegmatites was one of the original minerals of the common pegmatite before the albite replacement. Being

more resistant to the replacing solutions than potash felspar, the tourmaline is only corroded and replaced partially at the borders.

Garnet, though not a common mineral of the pegmatites, is found in some specimens. It shows signs of corrosion and has been " eaten into " by albite. It seems probable, therefore, that garnet, like black tourmaline, is one of the accessory minerals of the original pegmatite, present before the replacing solutions became active. This suggestion is supported by the fact that in common pegmatites garnets may often be found embedded in the potash felspar.

Muscovite, the common, colourless variety, is, in part at least, one of the constituents of the original common pegmatite. There are two other varieties, however, one apple-green in colour and the other dark grey, in curved plates and with a metallic appearance, which both appear to have replaced albite and so are to be included among the later minerals. It has been suggested that the variety showing curved faces is zinnwaldite. Though it may contain a small proportion of lithium, the percussion figures and analyses do not warrant the use of this name.

Quartz is, of course, among the original minerals of the common pegmatite. This quartz has been partially replaced by albite. Later generations of quartz have been deposited by replacement with and after the albite up till the last stages of hydro-thermal activity.

That pegmatites containing albite and rare minerals are the result of replacement by solutions acting on the minerals of common pegmatites has been suggested in recent years by Schaller (11) and Hess (12), followed by several later investigators. Though the present writer was not at first favourably impressed by this conception, detailed work has revealed evidence of such convincing character that he now believes that this process has been a dominant factor in the production of the complex pegmatites in this area. Direct crystallization cannot account for the mineral relationships as revealed by both macroscopic and microscopic examination.

Albite seems to have been the first and most abundant mineral to be deposited by replacement and to have heralded the arrival in many cases of rarer minerals. The minerals now found may, therefore, be divided into two groups according to whether they were present in the common pegmatite before albitization or were deposited later by replacement of albite or other earlier minerals. The minerals of the common pegmatite previous to albitization include quartz, orthoclase, microcline, apatite, muscovite, biotite, black tourmaline, and garnet. The minerals deposited by replacing solutions include albite, quartz, cassiterite, tantalite, some of the beryl, spodumene, lepidolite, amblygonite, coloured tourmaline, several varieties of muscovite, monazite, uraninite, topaz, and a number of rarer minerals not dealt with in this paper.

We must not draw too strict a line between those minerals of the common pegmatite and those deposited by replacement. The replacement may have followed without a break after the crystallization of the earlier minerals of the pegmatite, and indeed there may have been some replacement of one mineral by another before the albitization. However, the abundant albite replacement does seem to be a necessary preliminary to the deposition of those minerals containing rare elements which have aroused so much economic and scientific interest.

Texture.

One of the most interesting features of the complex pegmatites of this area is the presence of coarse- and fine-grained material side by side. Not only do we find both types of material forming different parts of the same dyke or sill, but they appear in the same hand-specimen and even in the same thin section.

Let us consider first the cases where fine-grained material occupies a distinct portion of a dyke or sill. The fine-grained material in the cases discussed is always that described above as "albite-aplite". In the large sill at Bernic Lake, revealed by diamond drill, albite-aplite forms the upper part, while the lower portion consists of coarse common pegmatite, in which, however, the felspar, from its external form originally microcline, is now albite. In other cases the albite-aplite forms the lower portion of the sill, the upper part being coarse pegmatite, and in some cases separated from the aplite by a zone rich in lithium minerals. At the Silverleaf lithium deposit the albite-aplite, showing a rich red colour in place of the usual white or grey colour, forms the outer zone, while the central part is occupied by coarse material containing lithium minerals. In many of these cases the aplite shows a faint banding, marked by lines of minute garnets, parallel to the contact with the adjoining coarse phase. This feature suggests that some pressure had been exerted while the aplite was still in a viscous or semi-crystallized state. The explanation of the sharp difference in character may be something as follows: The magma containing albite and rare elements was intruded along one of the walls of a dyke, sill, or stock of common pegmatite. After much of the albite had started to crystallize out pressure was exerted transverse to the walls (possibly merely by the force of crystallization). This pressure resulted in the squeezing off of the remaining liquid portion and the packing together of the albite crystals. The removal of the liquid would prevent further growth of the albite crystals, resulting in a fine-grained rock showing signs of pressure and not containing a significant proportion of rare elements. The liquid portion, consisting of much water, some albite and quartz still in solution, and also the rare elements such as lithium and tin, was forced out into the adjoining common pegmatite. Since some of the minerals of the common pegmatite were unstable in the solution they were dissolved

and replaced by albite, lithium minerals, etc., present in the solution. The mobility and high water content of the solutions would allow large crystals to grow by replacement at a relatively low temperature.

Thus here again, as in the case of common pegmatites and aplite, a squeezing process is thought to account for the sharp difference in texture which is so puzzling a feature.

It was mentioned that coarse- and fine-grained material are even more intimately mixed in some cases. Often a specimen containing coarse albite and other minerals is impregnated with stringers and pockets of albite even finer-grained than in the massive albite-aplites mentioned above. Microscopic examination leads one to conclude that the fine-grained albite has replaced the coarse in these cases. It seems probable that the material is of a different origin to the more massive albite-aplites. No very definite evidence of its origin could be found, but it is likely that the finest-grained material represents a reworking of the albite by circulating waters after most of the reactions had ceased.

There are, therefore, in this district three distinct types of texture of albite : (1) The massive aplitic type, often with garnets, probably produced by the squeezing off of the water with volatile rare elements and some dissolved silicate, during crystallization. (2) The coarse type, mainly replacing common pegmatite minerals. (3) The finest type, in small pockets and stringers, later than the rest and possibly due to rearrangement by hot waters.

Conclusions.

Both the mineral relationships and the well-marked variation in texture combine to refute the conception that complex pegmatites of this type were formed by the direct crystallization of an intruded magma. The fact that we can often trace a part of a dyke containing albite and rare minerals into common pegmatite, and the evidence of microscopic relationships across the gradation, point to the conclusion that the original material of the whole dyke was common pegmatite and that the complex parts are subsequent alterations representing the final stage of igneous activity.

Hess (13), one of the first writers to put forward a theory of replacement for pegmatites, considers that the original intruded material solidified as quartz and felspar, but in the centre of the dyke a stream continued to flow from the original source, bringing solutions which replaced the earlier-formed material with new minerals. Schaller (14), in the same year (1925), working independently, put forward a somewhat similar theory but backed up with more detailed observation. He described pegmatites in San Diego county of California, worked for gem tourmaline and other lithium minerals. In many cases the upper part of a flat-dipping dyke consists of common pegmatite or " graphic granite ",

the lower part of albite with subordinate quartz and parallel lines of garnets, and in the middle the " pay streak " containing the lithium minerals. Schaller conceives the whole dyke to have been originally " graphic granite " and the sodic solutions, carrying also lithium and other rare elements, to have worked up the foot-wall of the dyke or sill, replacing the earlier minerals. Schaller carries his argument still further in suggesting that even the graphic granite is not the original material of the dyke, but has replaced a still earlier fine-grained orthoclase rock. The present writer cannot support this last suggestion, but, so far as the complex parts of the pegmatite are concerned, Schaller's hypothesis receives much support from the Manitoba occurrences.

Landes (15), slightly later in the same year as Hess and Schaller published their papers, described pegmatites in central Maine, U.S.A., and suggested a replacement hypothesis to explain the more complex occurrences. He divides the minerals into five classes, the first being minerals which have crystallized out from the original intruded magma, the next three classes containing minerals deposited by replacement from hydro-thermal solutions, and in the last class minerals formed by supergene alterations. Albite, the lithium minerals, and most of the rare pegmatitic minerals, are included in the three hydro-thermal classes. Landes is in agreement with Schaller and Hess in his general idea of replacement, but differs in his sharp separation of the process into distinct stages.

It is interesting to note that in South Africa Wagner (16) independently suggested that replacement played an important part in the production of the tin-bearing pegmatites.

If we are to accept a replacement hypothesis for complex pegmatites we must find an explanation for the presence of solutions so rich in albite and carrying such rare elements as lithium, tin, tantalum, and beryllium. It has been suggested that the high soda content of these complex pegmatites is due to the extraction of this element from the enclosing country rock. The Manitoba occurrences do not support this suggestion. Many complex dykes occur in impure quartzites with a low soda content, and, conversely, the andesites, with a high soda content, contain many pegmatites with only potash felspar, as well as some complex dykes with albite. A more probable explanation may be derived from a study of the differentiation of a normal granite magma. Bowen (17) has shown that in a certain stage of the differentiation of a granite magma reactions take place involving the breaking down of polysilicate to orthosilicate molecules, including $KAlSiO_4$. The precipitation of $KAlSi_3O_8$ and $KAlSiO^2$ in mica and SiO_2 as quartz results in the concentration in the remaining liquid portion of $NaAlSiO_4$ and volatile constituents such as water, chlorine, etc., with their compounds. This liquid, if separated off by crystal settling or by squeezing would, on cooling, precipitate nepheline and form nepheline-syenite. If, however, the liquid is mixed with free silica,

albite results instead of nepheline. Although these facts were produced by Bowen to explain the origin of nepheline-syenites and other major alkaline intrusives, it has occurred to the present writer that the same physical-chemical principles may apply in the somewhat later stage of the pegmatite magma. The fact that $NaAlSiO^4$ and volatile constituents tend to be preserved in the liquid after much of the potash felspar, mica, and much of the quartz has crystallized, explains very perfectly why the quartz-microcline-mica pegmatites are, in some places, at a later stage, attacked by soda-rich solutions, resulting in replacement first by albite, and then by minerals containing, or associated with, volatile elements. The presence of abundant silica accounts for the $NaAlSiO_4$ molecule always being precipitated as albite and not as nepheline or other felspathoid.

There is thus no need to search for markedly alkaline major intrusives nor for soda-rich country rock in the vicinity to explain the abundance of albite in the last-formed material of some pegmatites.

Some experiments were carried out in connection with this problem to ascertain whether any of the minerals present in these complex dykes had a markedly lowering effect on the melting points of the rarer pegmatitic minerals and, in particular, of cassiterite. Cassiterite was heated in crucibles to temperatures up to 1,600° C. after being ground and mixed with various mineral associations. It was thought possible that such minerals as tourmaline, containing volatile elements, might exercise a lowering effect on the melting points of other minerals. Very little such effect was noticed. Cassiterite was found to have a melting point above 1,600° C. (this result is in accordance with that obtained by Ruff (18) as opposed to the melting point given by Cusack (19) and Miller), and most of the other rare minerals also had high melting points. In a silicate melt of felspar and quartz cassiterite remained quite unaltered up to 1,400° C.; between 1,500° C. and 1,600° C. it underwent a change, becoming isotropic and granular, but it was not dissolved to any marked extent. No difference was noted on the addition of minerals containing volatile elements with the exception of fluorite, which increased the solubility of cassiterite to a limited extent. The dissolved cassiterite, on cooling, crystallized out as needles, visible under the microscope. Fluorite, however, is not a common mineral in pegmatites, and was hardly ever seen in the Manitoba occurrences.

Now most of the minerals of the complex pegmatites must have been deposited at comparatively low temperatures, at least below 575° C., since the quartz, except for that in earlier graphic intergrowths, is of the low temperature type, and much of it is older than the albite and rare minerals. Since the minerals have high melting points and have so little effect in the mutual lowering of melting points, we are again drawn to the conclusion that they must have been deposited from relatively weak, aqueous solutions.

SUMMARY.

From the conclusions regarding the formation of complex pegmatites from the field and microscopic evidence, the following sequence of events is suggested :—

Towards the end of the solidification of a granite magma a liquid remains, having the general composition of a common pegmatite, but with small quantities of sodium and some rarer elements. By squeezing during crystallization this magma is separated into two distinct parts, one of which forms common aplite dykes. The other, more aqueous portion, when tapped by fissures, solidifies more slowly to form dykes, sills, or stringers of common pegmatite. During this solidification the albite (in solution), together with rare elements and their compounds, is concentrated in the remaining liquid portion, which now contains a very high proportion of water. This aqueous solution begins to migrate up the dykes or sills of common pegmatite, possibly even before the latter has completely solidified, showing a preference for the foot-wall, and begins to replace the earlier minerals, The first stage is the replacement of potash felspar, either microcline or orthoclase, by albite. Later there is a replacement of albite and sometimes of earlier minerals by spodumene, lepidolite, cassiterite, tantalite, etc. Cassiterite, possibly due to being carried in combination with a volatile element tends to be deposited in the uppermost part of the dyke or sill, where, however, some albite replacement has always preceded it.

In some cases the sodic solution, instead of replacing earlier minerals particle by particle, seems to have dissolved and removed the whole of the lower part of a dyke or sill, so that the new material (largely albite) crystallizes freely as in a true intrusion. In such a case, after much of the albite has crystallized, either due to the pressure from the walls of the body or by the force of crystallization itself, the remaining liquid portion is squeezed out into the upper part of the body, leaving behind albite-aplite. In the upper part of the body what albite still remains in solution will be deposited by true replacement, followed, at a slightly lower temperature, by lithium minerals and other soluble compounds. It will be apparent that in such a case the original sodic solution containing the albite and rare minerals is subjected to a further process of concentration, the rare minerals being removed from the bulk of the albite. This feature may explain why those bodies richest in lithium minerals so often show a fine-grained albite-aplite with banding indicating squeezing during crystallization, sharply contrasted with the coarse part containing the lithium itself. The Silverleaf deposit is an excellent example of such a case, but it is also seen in some of the smaller sill-shaped bodies, not to mention the remarkably similar occurrences described from California by Schaller.

THE RELATIONSHIP OF TIN-BEARING PEGMATITES AND TIN VEINS.

Cassiterite is one of the few minerals to be found in pegmatites and in veins, apart from such " gangue minerals " as quartz and felspar. The problem of the relationship of the pegmatites containing cassiterite to the true tin veins is an interesting one. In the first place we can dismiss the idea of a *common* pegmatite grading either vertically or horizontally into a vein containing cassiterite. For one reason the quartz veins that can be traced into pegmatite are, wherever seen by the writer, entirely barren of ore minerals. Secondly, cassiterite does not, as a rule, occur in common pegmatite. It is found in the complex pegmatites where albite has replaced most of the original minerals. It seems probable, therefore, that the connection of the tin veins to the tin-bearing pegmatites is by the further migration of the solutions which have attacked and replaced the common pegmatite. The replacing solutions originate in the pegmatite and tend to be active within the pegmatite body to begin with. There is no reason, however, why the activities of the solutions should be confined to the limits of the original dyke or sill. Landes (20) believes that in Maine they have encroached far beyond the original pegmatite boundaries, forming irregular bodies. In Manitoba the activities of the solutions seem to have kept within the original pegmatite boundaries for the most part, but in one case in particular, at a cassiterite segregation at the top of an arched sill, small veins about 3 inches wide, rich in cassiterite, and containing also much quartz and some albite and muscovite, run off upwards from the sill. These may be replacements of common pegmatite stringers or they may be direct fillings of fissures. Apart from its visible connection with a complex pegmatite it would be difficult to say whether such a stringer should be called a true tin vein or a tin-bearing pegmatite. It thus seems possible that the final replacing solutions, after depositing nearly all the albite, the lithium minerals and associated compounds and some of the cassiterite and quartz in the pegmatite itself, may migrate on, still carrying tin and silica, to form quartz-cassiterite veins in fissures at higher levels.

It is, of course, not the case that all tin veins are formed from solutions that have passed through pegmatites. It seems certain, especially in the cupolas of batholiths, that the tin-bearing solutions responsible for the veins are concentrated directly from the solidifying granite. It is obvious, however, from field relationships, that in many cases there exists a very close connection between complex pegmatites and tin veins.

The genetic relationship between tin veins and pegmatites is seen in a broad way in noting characteristic occurrences at different horizons of erosion in stanniferous regions. Thus, when erosion has reached such a level that all the sedimentary or volcanic covering of the granite batholith is removed except very narrow roof-pendants, then only common pegmatites and aplites are found. If the roof-

pendants are not worn down to such narrow remnants, then we may find complex pegmatites as well as those of the common type. The Winnipeg river area and the Black Hills of South Dakota are examples of this stage. If, however, erosion has only just exposed the cupolas on the roof of the batholith, as in Cornwall, then tin veins are characteristic, accompanied by quartz-porphyry dykes, while pegmatite dykes are small and relatively unimportant. Thus in an area where cassiterite is present in complex pegmatites, not only does it not necessarily follow that tin veins will also be found, but it is actually unlikely, since erosion has passed through the horizon in which they would normally occur.

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REFERENCES.

(1) SCHALLER, W. T. *Amer. Jour. of Science* (5), x, 1925, pp. 269–79.
(2) HESS, F. L. *Eng. and Min. Jour. Press*, cxx, 1925, pp. 289–98.
(3) MILLER, W. J. *Jour. of Geol.*, xxvii, 1919, pp. 27–54.
(4) SPURR, J. S. *The Ore Magmas* (McGraw-Hill), 1923, pp. 310–15.
(5) BARROW, G. *Quart. Jour. Geol. Soc.*, xlix, 1893, pp. 330–56.
(6) HARKER, A. Ibid., l, 1894, pp. 311–36.
(7) BOWEN, N. L. *Jour. Geol.*, xxvii, 1919, pp. 407–10.
(8) SCHALLER, W. T. Op. cit.
(9) HESS, F. L. Op. cit.
(10) WRIGHT, J. F. *Geol. Surv. Canada, Summ. Rept.*, Part B, 1924.
(11) SCHALLER, W. T. Op. cit.
(12) HESS, F. L. Op. cit.
(13) HESS, F. L. Op. cit.
(14) SCHALLER, W. T. Op. cit.
(15) LANDES, K. K. *Amer. Mineral*, x, 1925, pp. 355–417.
(16) WAGNER, P. A. "The Union of South Africa," *Handb. d. regionalen Geol.*, vii, 7*a*, 1929, 193–200.
(17) BOWEN, N. L. *Jour. Geol.*, xxiii (Suppl.), 1915, pp. 54–6.
(18) RUFF, O. *Zeit. Anorg. Chem.*, 83, 1913, p. 373.
(19) CUSACK, R. *Proc. Roy. Irish Acad.* (3), iv, 1896, p. 399.
(20) LANDES, K. K. Op. cit.

REVIEWS.

ENGINEERING GEOLOGY. By H. RIES and T. L. WATSON. Fourth edition. pp. vi + 708, with 253 figures. New York: Wiley; London: Chapman and Hall. 1931. Price, 25*s*.

THE chief additions made in this fourth edition consist of a number of extra references, thus bringing the book up to date. Also a new chapter has been inserted in the middle, with a rather clumsy method of separate paging (pp. 446a–446t) on the geology of reservoirs and dams, a subject which does not seem hitherto to have received much attention in general textbooks.

GEOLOGY OF PETROLEUM. By W. H. EMMONS. Second edition. pp. xi + 736, with 435 text-figures. London: McGraw-Hill Co., 1931. Price, 30*s*.

IT is no easy task to issue a new edition of a book on Petroleum Geology with a gap of ten years between the two editions. These ten years, 1921 to 1931, have not only seen a vast increase in our knowledge of the subject, but also remarkable changes in the relative importance of different countries as commercial producers of petroleum. To take two striking instances: in 1920, Mexico ranked second amongst oil-producing countries with nearly 22,000,000 tons in that year; by 1930 her production was just over 5,000,000 tons and had fallen to seventh place. Even more striking was the rise over the same period in the Venezuelan production from 70,000 tons to over 18,000,000 tons, placing her now as second in the list of producing countries. While the importance of a country from the point of view of oil geology is not necessarily in proportion to its production, such changes, especially in the way of increased production, necessitate considerable alterations in treating of the subject. Dr. Emmons accomplishes his task partly by the expansion and partly by the re-writing of the first edition, and is to be congratulated on the results.

In the present edition the first ten chapters (as against fourteen in the first) are devoted to the general considerations of the distribution of oil geographically and geologically, its probable origin, and the geological conditions required to give rise to commercial concentration. As regards the origin of oil, the author's conclusions are "that oil is derived from organic matter of both animal and vegetable origin, marine and non-marine, and that it is probably derived from the remains of many kinds of plants and animals. The almost constant association of oil with salt water supports the theory that most oil deposits, if not all of them, have accumulated in the sea".

In this section of the book the author, as in the earlier edition,

keeps strictly to the theoretical side, so far as geology is concerned; he does not touch on practical field geology, nor, as he points out in the preface, does he include geophysical methods beyond a passing reference on page 64. Although, perhaps, one misses a fuller reference to those more outstanding advances in field geology which have been largely due to the search for oil, he has probably drawn the line wisely, as practical field methods, including geophysical surveying, do not affect the theory of oil geology, and are best treated separately. Considerably more attention is given to that highly vexed subject of oil occurrence and carbon ratios brought forward by David White, and the author's summary is cautious and non-committal.

As in the first edition, the main part of the book, pages 162–567, is devoted to a description of the oilfields of the United States, while the rest of the world is dealt with in pages 568–714. Throughout, the information is brought well up-to-date, and if perhaps one is inclined to feel that the rest of the world has been a little cramped in space to give room for the U.S.A., in justice one must admit that the ratio of space allotted is not so very different from the ratio of oil produced. In the main the description of oilfields and oil occurrences in the countries outside the United States, though somewhat brief, contains the main essentials.

Dr. Emmons is to be congratulated on the number of stratigraphical tables given throughout the book, and this feature alone gives great value to the volume as a book of reference, and this is largely increased by the number of sketch-maps and sections.

As previously, copious references are given to literature, but these references should have been more carefully checked. Possibly the reviewer has been unfortunate, but out of a dozen or so references verified, no fewer than three give the wrong year, viz., page 667, R. K. Richardson's paper on Persia is dated 1924 not 1928; page 616, E. M. Bailey's paper on the shale oil industry of Scotland was published in 1922, not 1927; and on page 595, Waring and Carlson's paper on Trinidad appeared in 1925, not 1923. One hopes that the rest of the references do not contain the same proportion of inaccuracies.

The printing of the book leaves nothing to be desired and, apart from the above-mentioned references, the text seems singularly free from errors, though a curious mistake occurs on page 616 where the age of the oil shales of Scotland is given as Lower Cretaceous.

The reviewer has used Dr. Emmons' book as a work of reference for the past ten years, and welcomes the appearance of this enlarged and up-to-date second edition.

JAMES ROMANES.

THE EXAMINATION OF FRAGMENTAL ROCKS. By F. G. TICKELL. pp. x + 127, with 51 illustrations. Stanford University Press and Oxford University Press, 1931. Price 23*s*.

IT is significant that the author of this work is Professor of Petroleum Engineering in Stanford University, California. This, of course, indicates that economic geologists are well aware of the importance of the study of sediments, a branch of petrography which has been woefully neglected in most academic schools. So far as the reviewer is aware, this is the most up-to-date book on the subject that has yet appeared: it includes even a useful section on the application of spectrography to mineral determination. While a certain number of small slips have been noted in the theoretical parts of the work, especially in the optics, the book as a whole is eminently practical. The author appears to have little use for " elutriators ", which after all are mainly an expensive method of making a simple job complicated and messy, and depend on the assumption that all grains have the same density. He pins his faith on the simple and commonsense processes of screening, panning, and bromoform separation with recourse to all refined modern methods of individual determination of minerals after separation has been effected. The discussion of screen-sizes is of special value at this moment, when the subject is more or less in the melting-pot in this country, owing to the virtual abandonment of I. M. M. screens (or sieves, as they are often called) and their replacement by American standards. In such a subject uniformity of practice is the most vital consideration.

While on the question of panning, it may be noted that the present reviewer has found that an ordinary 9 inch glazed porcelain evaporating dish, such as is used in all chemical laboratories, is by far the most efficient implement, as contrasted with pans and bateas, in ordinary petrographical work. " Heavy minerals " in the geological sense are mostly dark in colour, and can be seen against the white background, although in prospecting for gold and platinum the dark pan has, of course, its obvious advantages.

The sixth section of this book is occupied by a useful tabular description of the properties used in the identification of a number of common rock-forming minerals, and the last division consists of what is described in the preface as a " dichotomous classification . . . which makes comparatively simple and rapid the recognition of the species commonly found in clastic mineral aggregates ". This is undoubtedly the weakest part of the book. It is not set up in ordinary type, but reproduced from MS. by some kind of process, and quite frankly it cannot be read without an undue strain on the eyesight: it may be all right, but this must be left to those with better eyesight than the reviewer.

THE JAPANESE EARTHQUAKE OF 1923. By CHARLES DAVISON. pp. 127 + 6 plates and 32 diagrams. London: Murby & Co., 1931.

"FOR centuries to come, the first of September, 1923, will be one of the darkest days in the history of Japan. For, by the earthquake that occurred at noon on that day, half the capital of the Empire was laid in ruins, the principal seaport was destroyed, and about one hundred thousand persons were killed." In these words, Dr. Davison begins his simple and lucid account of what was a noteworthy event in the current geological history of Japan, as well as an appalling disaster in its human history. A voluminous literature has already accumulated around the earthquake and the investigation of its results, and English readers may well be grateful to Dr. Davison for his enterprise in compiling this admirable book from some forty Japanese reports and memoirs. The first part of the book deals with the ravages wrought by the earthquake and the great conflagrations that followed it, and with the economic aspects of the disaster. The second part, which constitutes two-thirds of the book, describes the seismological and geological phenomena. The epicentral area was located in Sagami Bay, in a region of uplifted fault blocks and depressed graben which has been subjected to movements from far back in the Tertiary up to the present time. Sagami Bay itself drops to a depth of 1,000 metres within three miles of the shore, and is traversed by a deep trench with steep high submarine walls running S.E. past the north end of Oshima. On the land this is continued as the Sakawa rift valley. The floor of the trench was deepened as a result of the earthquake by 300–700 feet. The submarine shelf on the N.E. was uplifted by 820 feet and that on the S.W. by 390 feet. These remarkable block-movements are of a hitherto quite unprecedented amplitude as far as actual observations are concerned. A very curious feature, of which the geophysical significance has not yet been made clear, is the fact that the movements on the land were of a totally different order. Most of the coast was permanently elevated, but the greatest uplifts were no more than 6–7 feet. This extraordinary contrast deserves further investigation. Enough has been said to indicate the spectacular nature of Dr. Davison's subject.

The book is of absorbing interest throughout from many points of view. Its non-technical style recommends it to the general reader, while its scientific accuracy ensures its welcome by geologists.

It has been remarked that motor-cars are more destructive to human life than earthquakes, but Tokio and Yokohama have motor-cars as well as earthquakes, and we may be thankful that we are spared the double menace.